Current Status and Future Innovations in Space Based Observations for Cryosphere Research

APECS *"Best Photo for the year 2020"*
Credit: Dr. Praveen K Thakur, ISEA-36

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About ISRO !

Foundation

https://www.isro.gov.in/

Dr. Vikram Sarabhai

Indian National Committee for Space Research, INCOSPAR -1962

Indian Space Research Organization, ISRO -1969

Big boost to ISRO: Chandrayaan-4, Venus mission, Indian space station and next-gen launch vehicle get Cabinet nod

By Singh Rahul Sunilkumar

Sep 18, 2024 04:23 PM IST

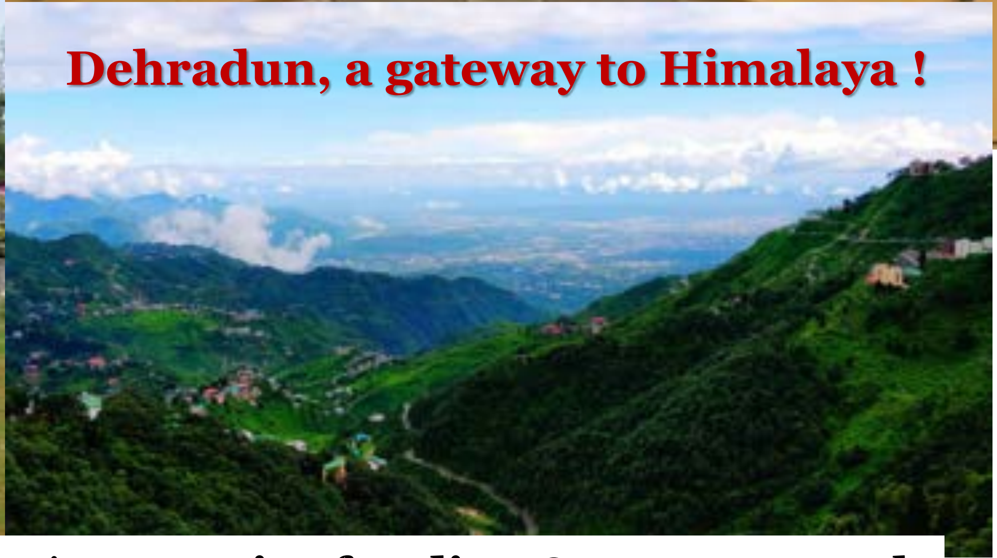
Chandrayaan-4, Venus orbiter mission, Indian space station and next-gen launch vehicle development plan get approval from Narendra Modi government.

ISRO-CNES Cooperation and joint Missions

- Sounding rocket launching facilities at Thumba (India) 1960s + Tech 1980-90s
- MeghaTropiques satellite for monitoring tropical atmosphere 2011-2022
- Satellite for ARGOS and ALTIKA (SARAL) 2013-2016, 2016 – (drifting orbit)

https://www.eoiparis.gov.in/page/bilateral-relations-with-france/

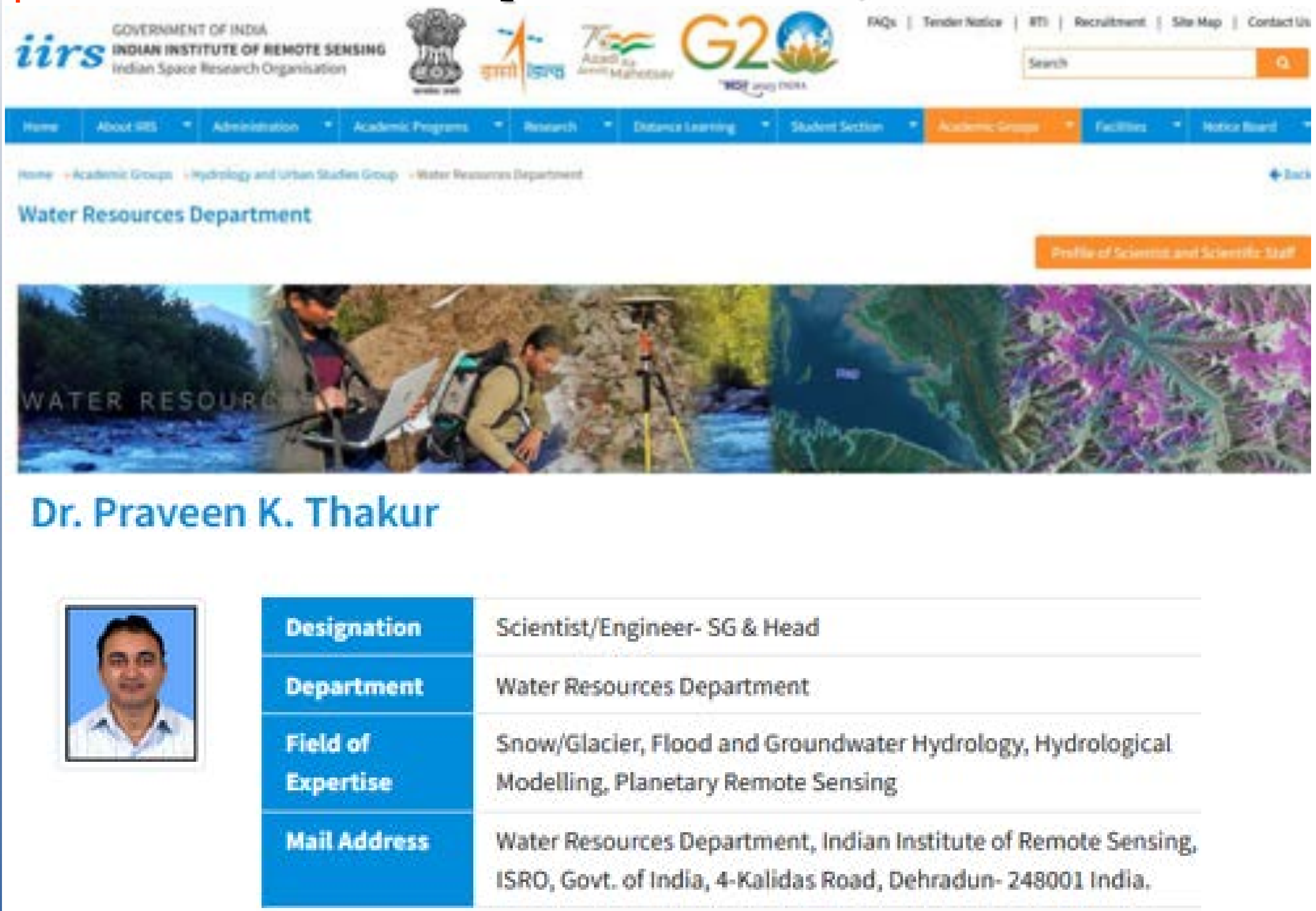
About IIRS, ISRO !



- The **Indian Institute of Remote Sensing (IIRS)** - is a constituent **unit of Indian Space Research Organisation (ISRO)**, Department of Space, Govt. of India.
- Since its establishment **in 1966**, IIRS is a key player for **training and capacity building in geospatial technology and its applications through training, education and research in Southeast Asia**. **Host to UN sponsored CSSTEAP, HQ, since 1995, https://cssteapun.org/**
- The training, education and capacity building programmes of the Institute are designed to meet the requirements of Professionals at **working levels, fresh graduates, researchers, academia, and decision makers. Academic collaboration with IIT Roorkee, FRI Dehradun, Andhra University, ITC, Twenty University, Netherlands for Post Graduate Programs**

About Myself !

Working as Scientist/Engineer at IIRS since 2004 & now Head of Water Resources Department of IIRS, Dehradun


iirs GOVERNMENT OF INDIA INDIAN INSTITUTE OF REMOTE SENSING Indian Space Research Organisation

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Water Resources Department

Profile of Scientist and Scientific Staff

WATER RESOURCES

Dr. Praveen K. Thakur

Designation	Scientist/Engineer- SG & Head
Department	Water Resources Department
Field of Expertise	Snow/Glacier, Flood and Groundwater Hydrology, Hydrological Modelling, Planetary Remote Sensing
Mail Address	Water Resources Department, Indian Institute of Remote Sensing, ISRO, Govt. of India, 4-Kalidas Road, Dehradun- 248001 India.

B.Tech – Civil Eng., (Hons): NIT Hamirpur
M.Tech – Water Resources Eng., IIT Delhi
PhD – Geomatics Engineering, IIT Roorkee

Space Studies Program 2019 at ISU Strasbourg, June-Aug. 2019

https://www.researchgate.net/profile/Praveen-Thakur-6
https://www.iirs.gov.in/Praveen_Kumar_Thakur
https://www.linkedin.com/in/praveen-k-thakur-01268731/

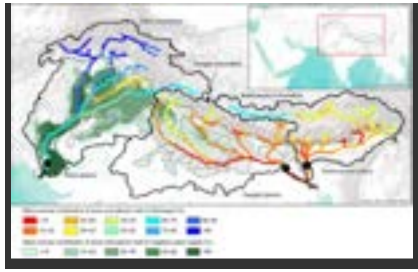

Participated in 2016-17 Summer Indian Scientific Expedition to Antarctica (ISEA-36)


Participated in 2019 Winter-Spring Indian Arctic Expedition at Svalbard


French connections !

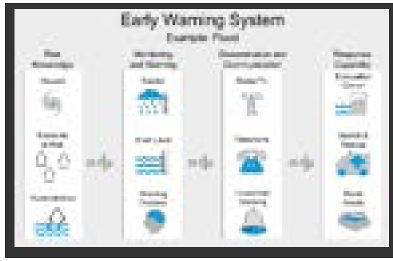
2 months at ISU Strasbourg For SSP19 Course + 1 week at Nice for ISPRS Congress June 2022

PRIORITIES AREAS OF CRYOSPHERE RESEARCH



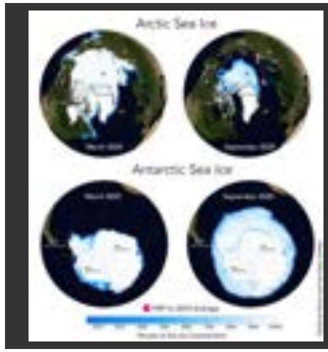
- Water availability in snow covered and glaciated basins
- Impact of anthropogenic changes and climate change

- Snow pack properties
- High resolution SCA
- Snowmelt



- Extreme Weather events Forecasting in high mountain watersheds
- Flood early warning systems

- Glacier status
- Glacier elevation
- Glacier zones
- Glacier mass balance

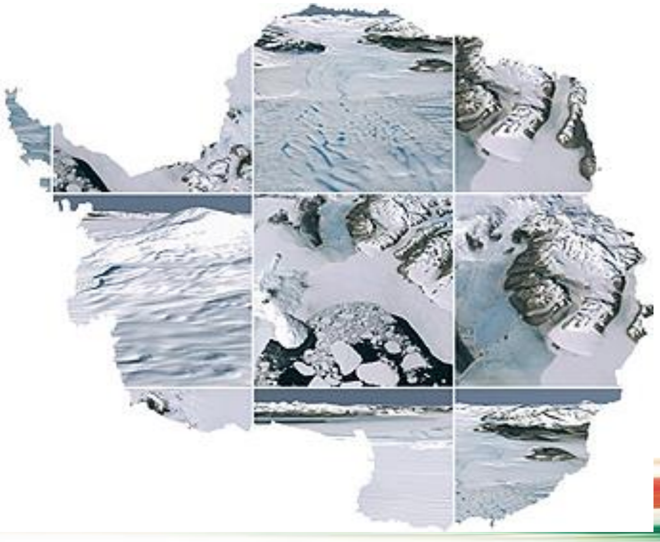
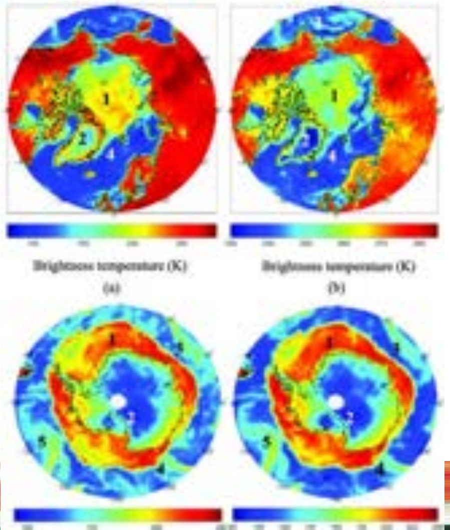
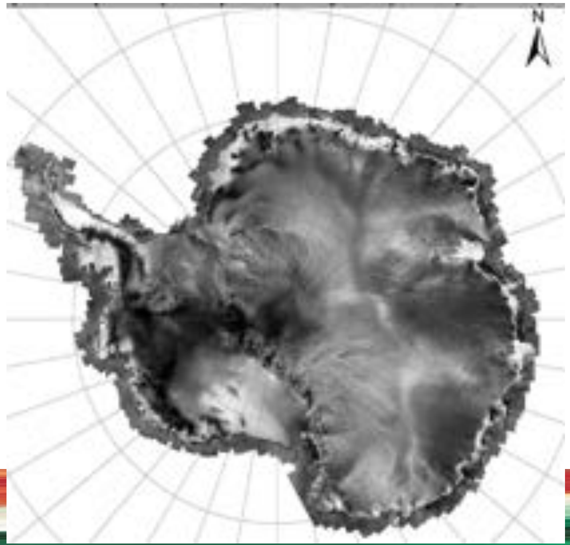


- Polar-Teleconnections with mid-latitudes
- Polar Sea-Ice variability
- Ice-sheet dynamics
- Ice shelf health and grounding line dynamics

- Snow, Glacier hazards monitoring & mitigation (GLOF, Avalanches, icefall etc.)

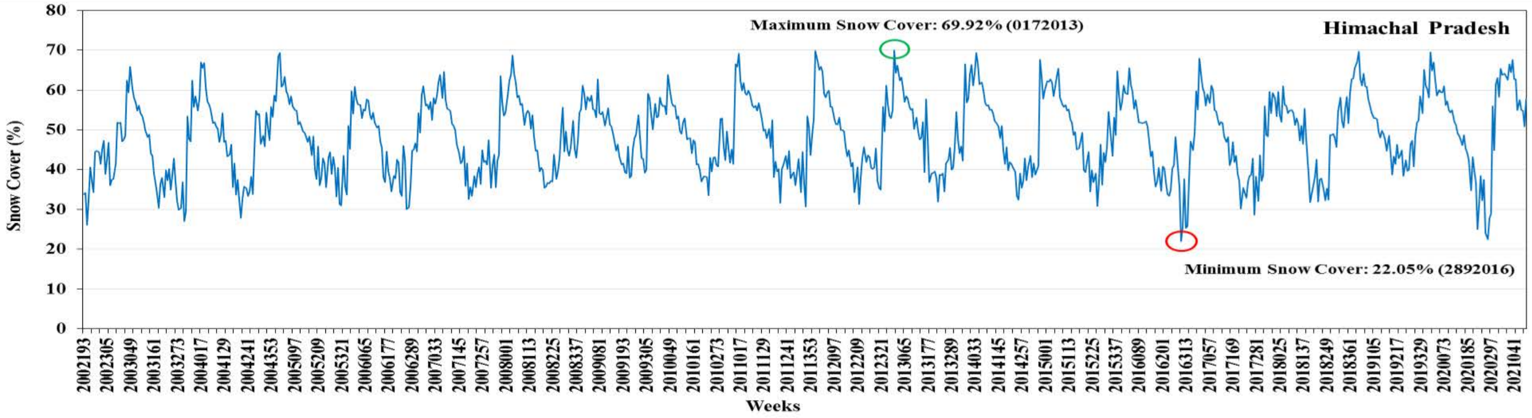
- Permafrost status and dynamics
- Global change Impact Assessment on various cryosphere components

Physical Basis for Remote Sensing of Cryosphere

Imaging System	Optical	Thermal	Microwave
Measurements	Reflectance (ρ)	Brightness Temp B(T)	B(T), Backscatter
Rationale	Spectral signature $\rho(\lambda) = \frac{\pi . L_{sensor}}{E_0 . \cos\theta_s}$	Planck's law $B(\lambda, T) = \frac{2\pi . h . c^2}{\lambda^5 . (e^{\frac{hc}{\lambda kT}} - 1)}$	Dielectric property $P_r = \frac{P_t . G_t . G_r . \lambda^2 . \sigma}{(4\pi)^3 . R^4}$
Parameters			

Innovative use of ML for creating the cloud free long term snow cover area using available optical satellite datasets

6



SCA used as direct input to snowmelt runoff models

Satluj Basin (upto Bhakra Dam)

Total Area (km2)	Max SCA (km2)	Min SCA (km2)
22275	15125 (66.99%)	4025 (18.07%)

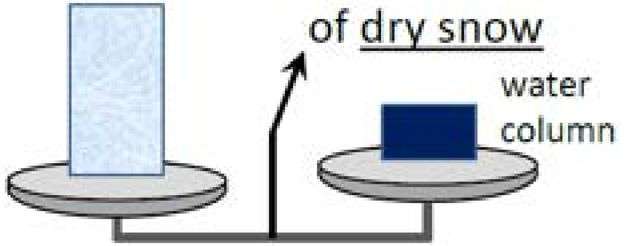
Total Area (km2)	Max SCA (km2)	Min SCA (km2)
22200	16415 (73.94%)	4590 (20.67%)

Total Area (km2)	Max SCA (km2)	Min SCA (km2)
5278	2825 (53.52%)	575 (10.89%)

IIRS has created long-term record (2000-23) of satellite based cloud free snow cover for entire Himalaya, including SCA for NWH region

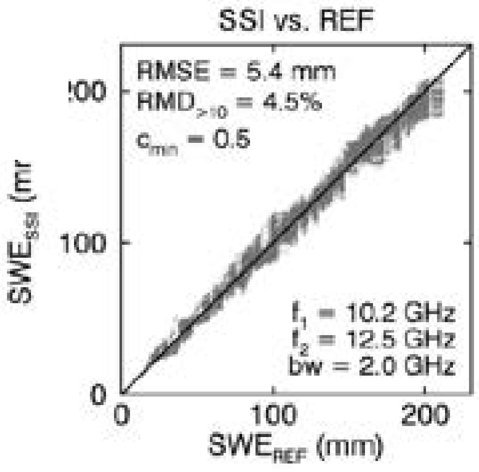
Advances in use of InSAR, DInSAR & PolInSAR in snow depth & SWE retrieval

Snow-Water-Equivalent of dry snow

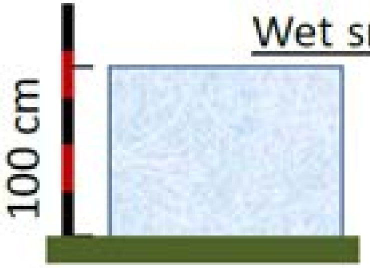


Differential Interferometry
(repeat pass)

$$\Delta\phi = -\frac{4\pi}{\lambda_0}\Delta Z\left(\cos\theta_0 - \sqrt{\epsilon - \sin^2\theta_0}\right)$$



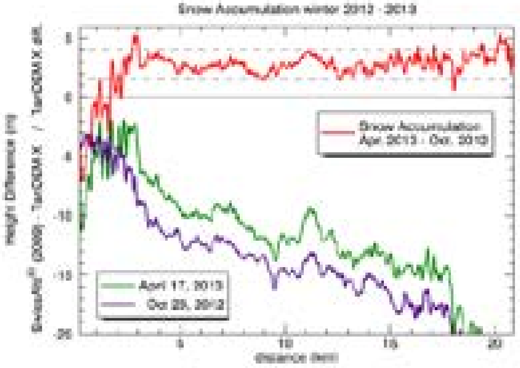
Wet snow depth



Single pass Interferomety

$$\Delta\phi = \frac{2\pi}{\sin\theta_{\mathrm{inc}}}\frac{B_\perp}{\lambda R_0}\cdot\Delta z$$

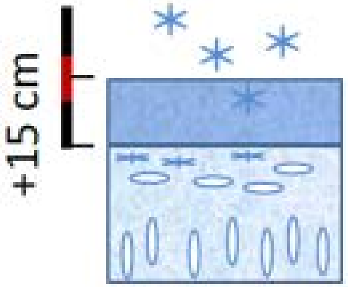
(dry snow not detectable!)



Leinss et al., 2013; 2015

Polarimetry of birefringent media

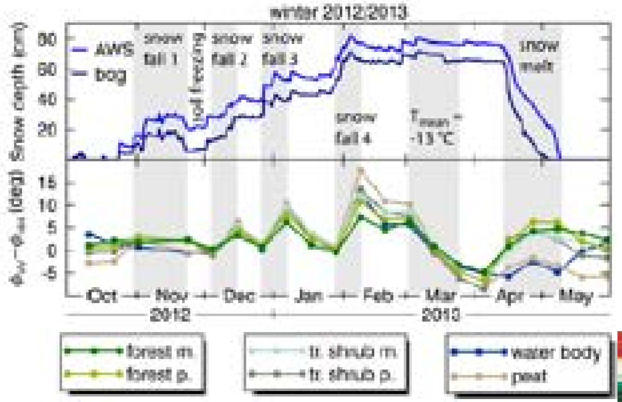
Fresh Snow depth



$$\Delta\phi = (-1)\cdot\frac{4\pi}{\lambda_0}\Delta Z\left(\sqrt{\epsilon_V - \sin^2\theta_0} - \sqrt{\epsilon_H - \sin^2\theta_0}\right)$$

Model: $\phi_{VV} - \phi_{HH} = f\,(\mathrm{SnowDepth}, T_{air})$

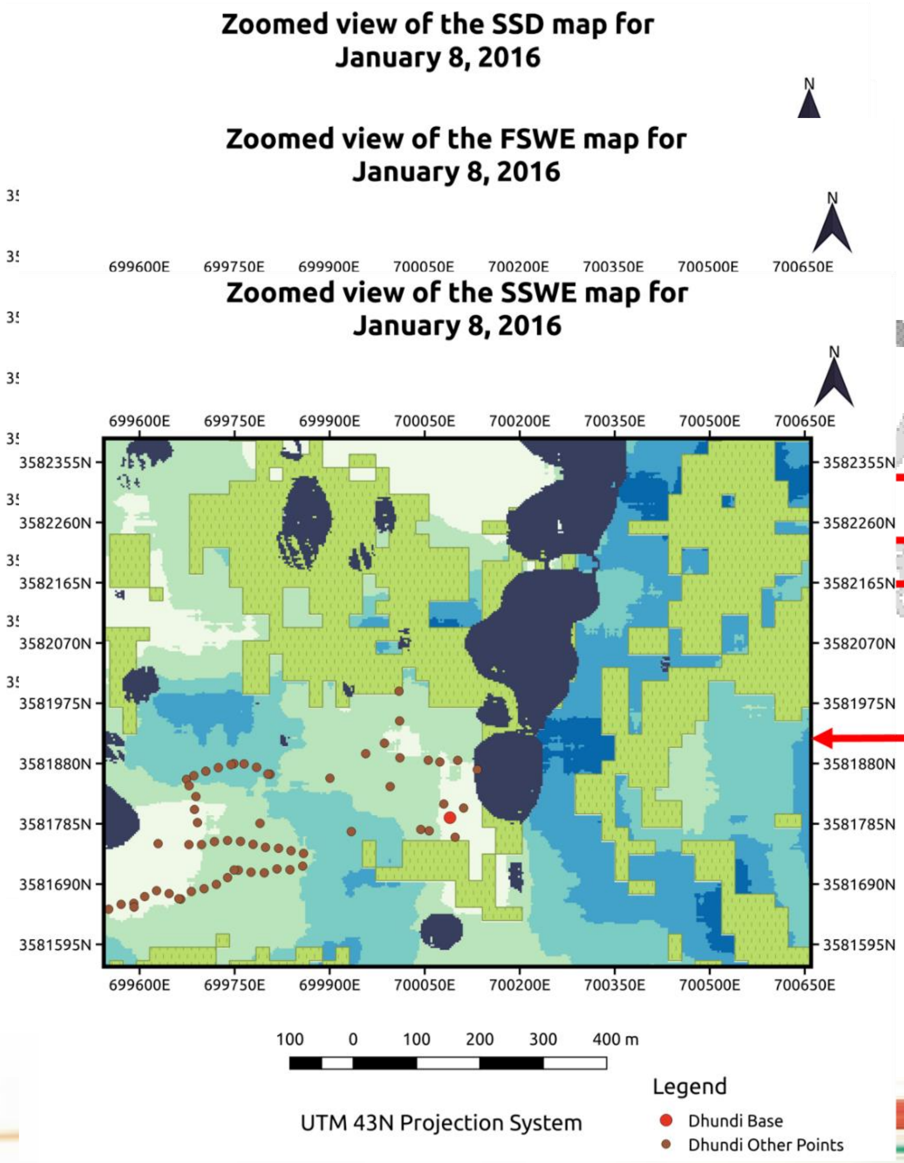
Anisotropy

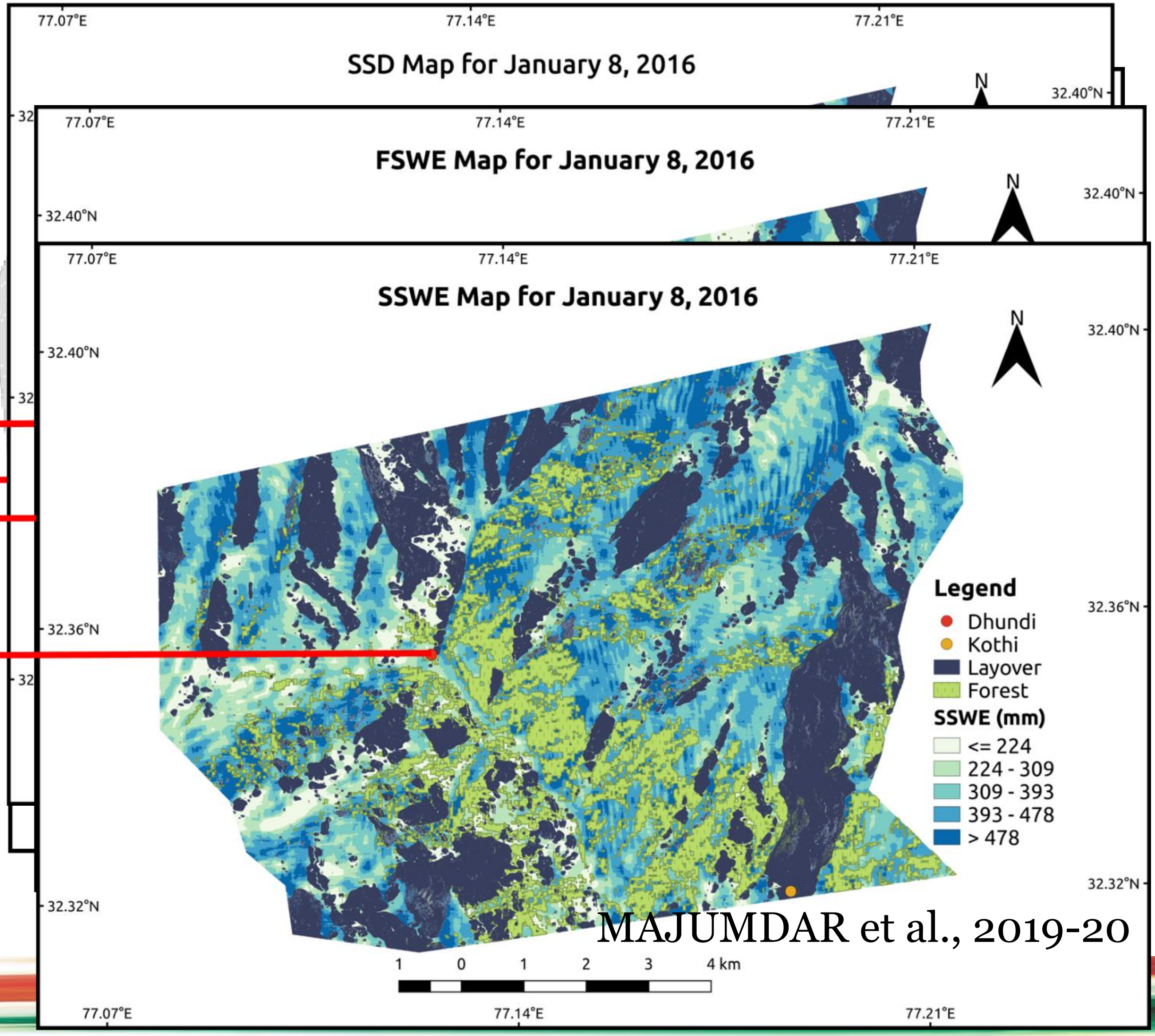


FSD, SSD, FSWE, & SSWE DERIVED USING PoLInSAR TDX DATA for Manali Wshed

FSD: Fresh Snow Depth SSD: Standing Snow Depth

FSWE: Fresh Snow Water Equivalent SSWE: Standing Snow Water Equivalent



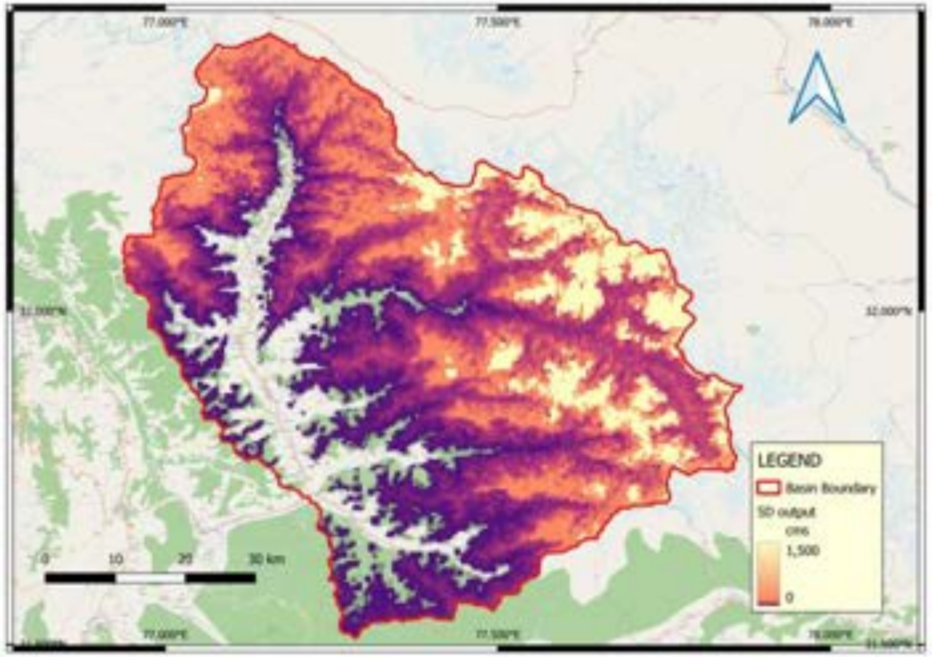


MAJUMDAR et al., 2019-20

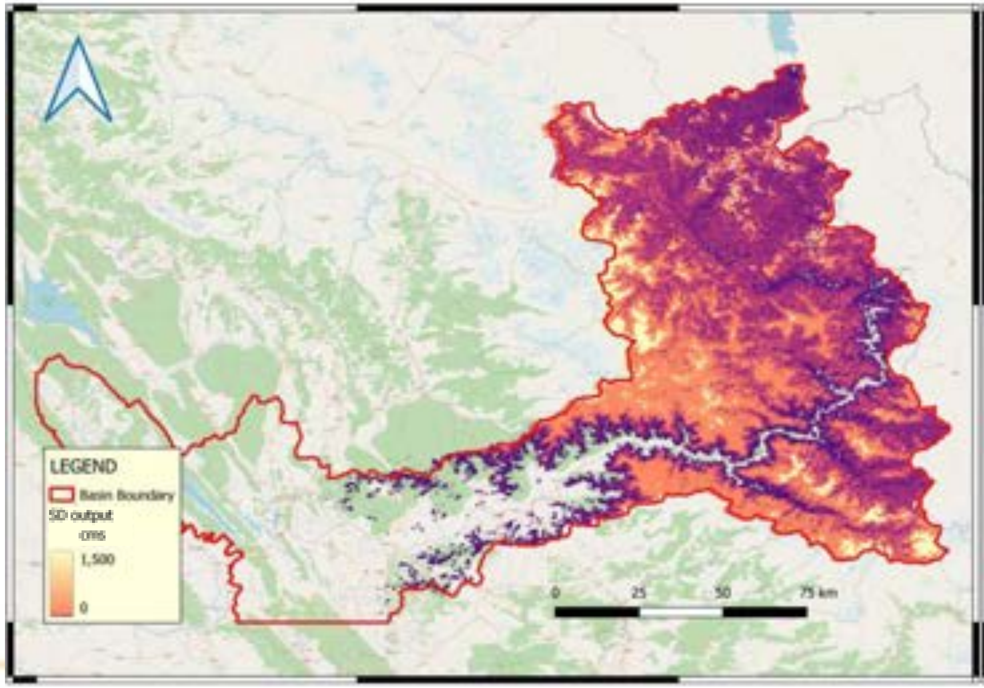
Multi-Sensor inputs, HMA data and machine learning based estimation of snow depth and SWE

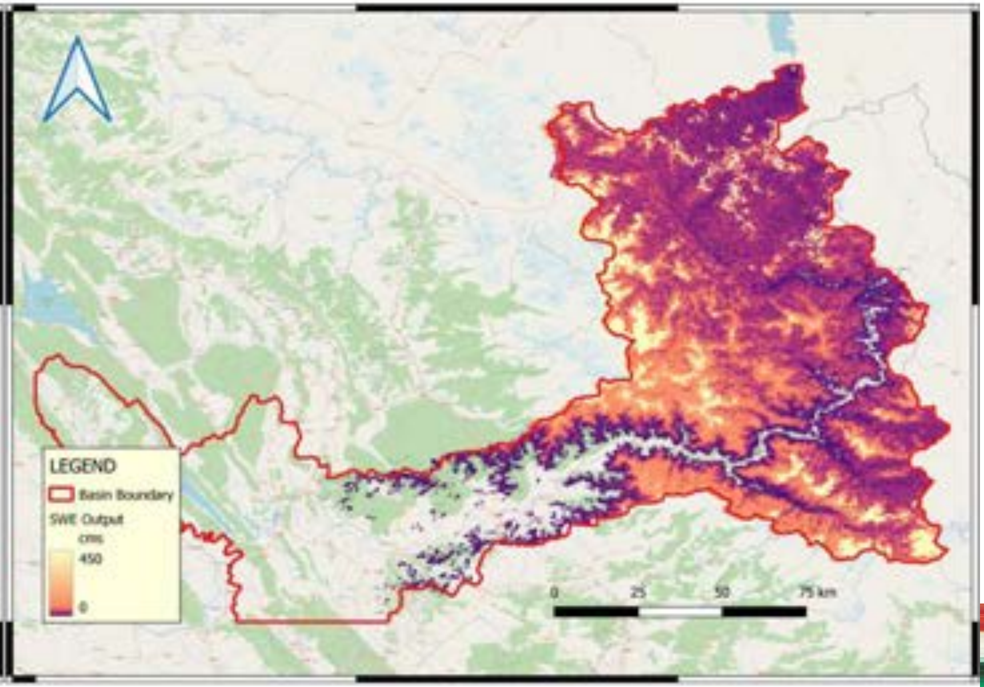
SD

R squared	0.811
MAE	7.447
RMSE	13.940



Feb 2017

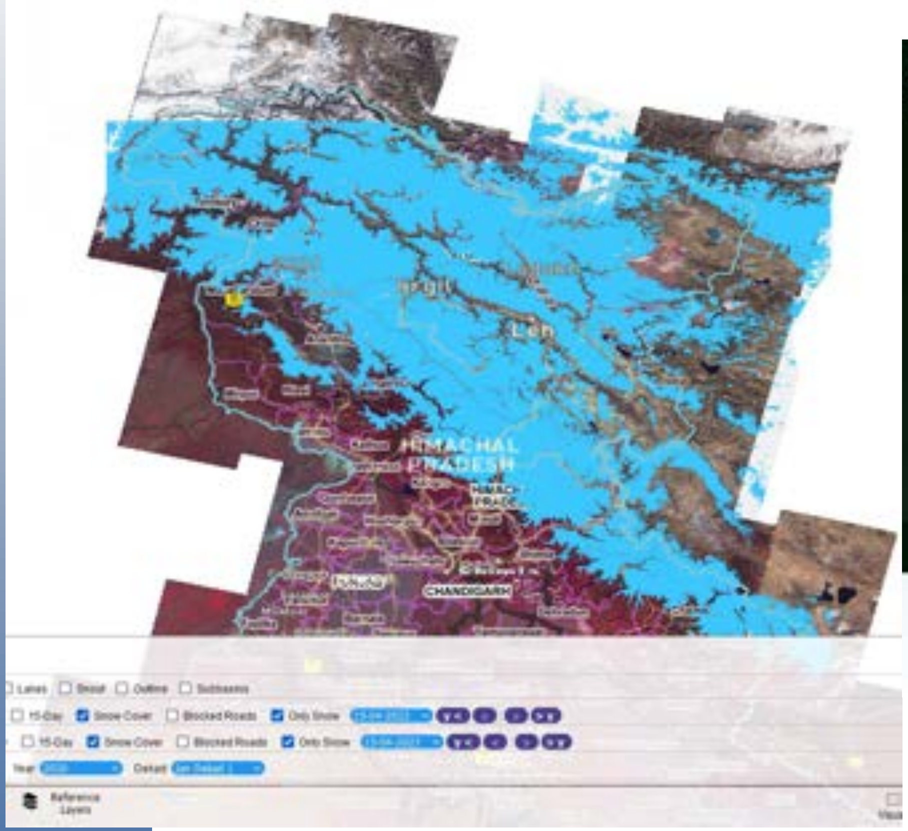


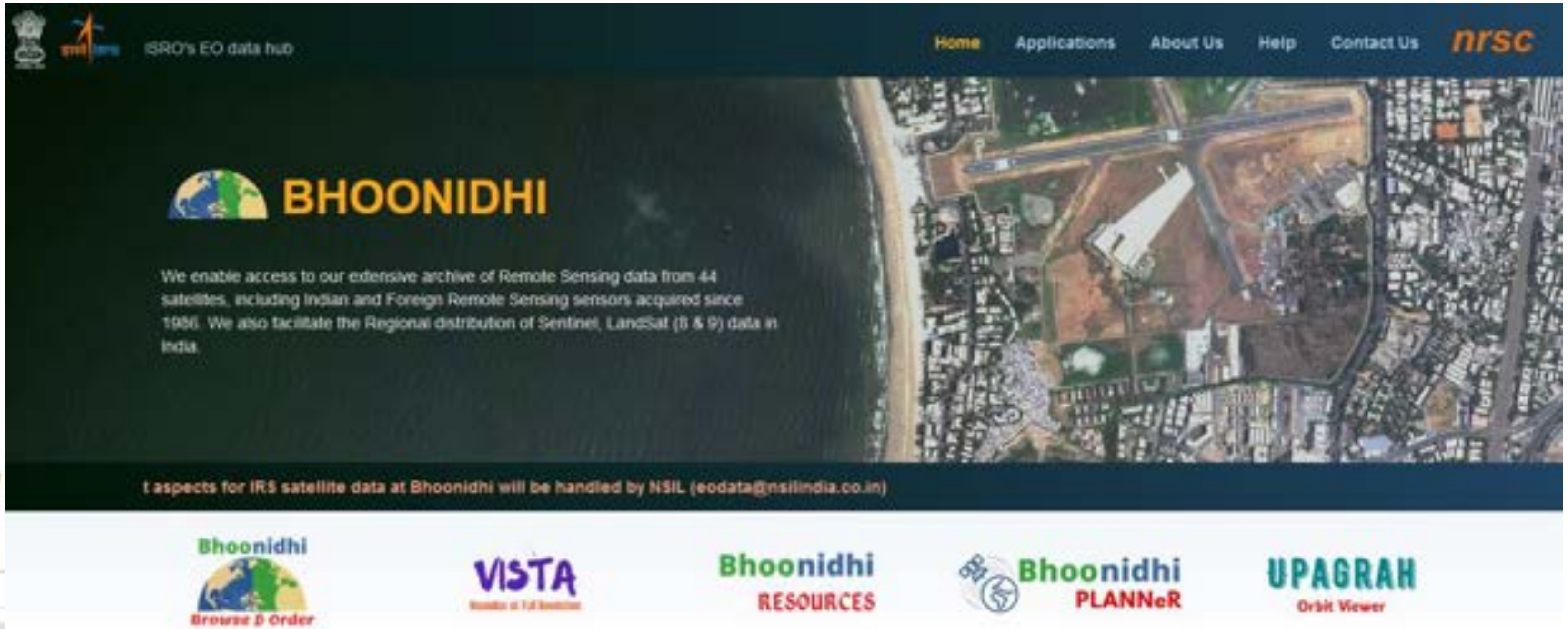


SWE

R squared	0.7080
MAE	2.750
RMSE	5.407

Near Real Time Snow cover monitoring from multi-sensors datasets

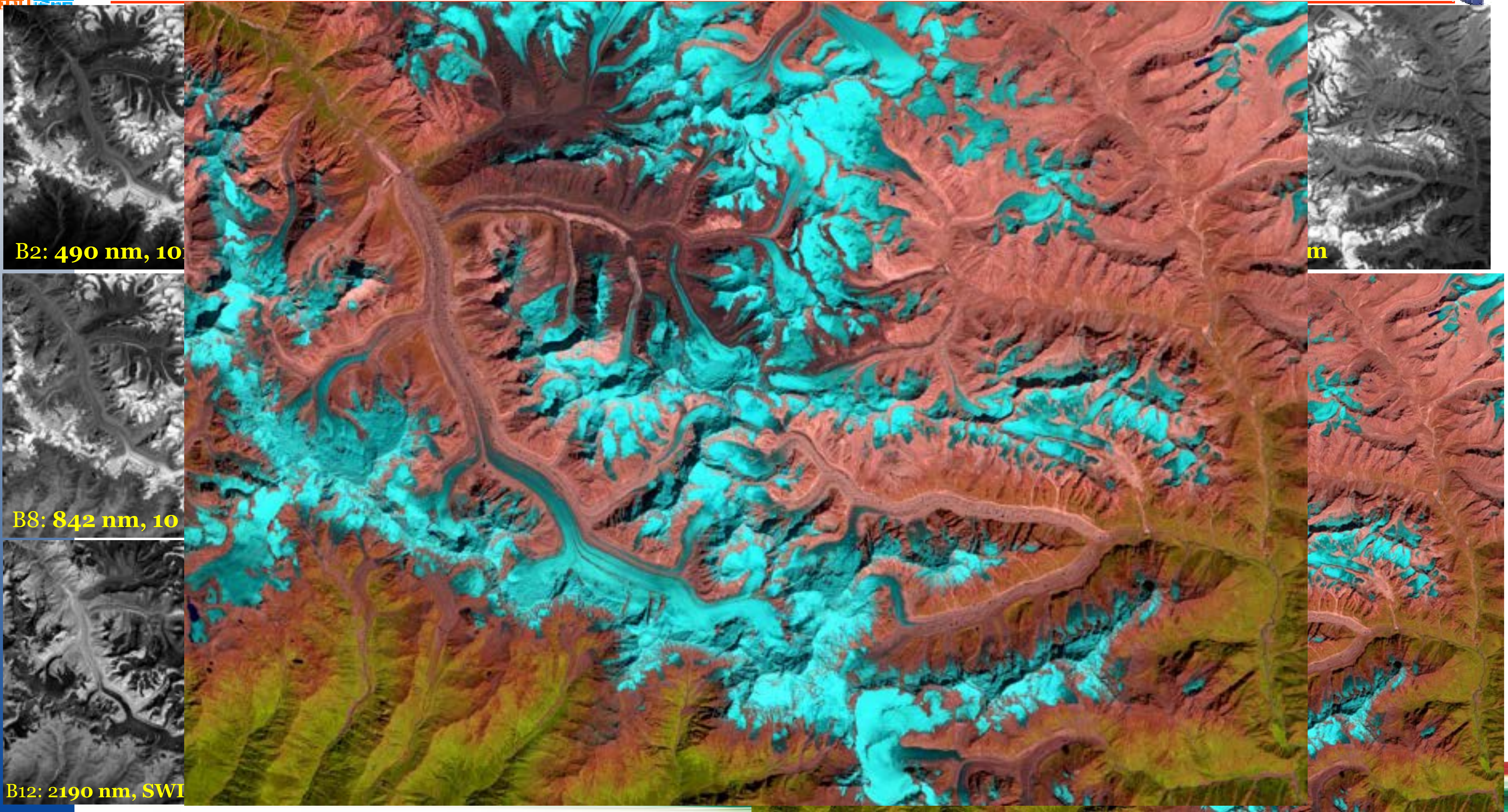




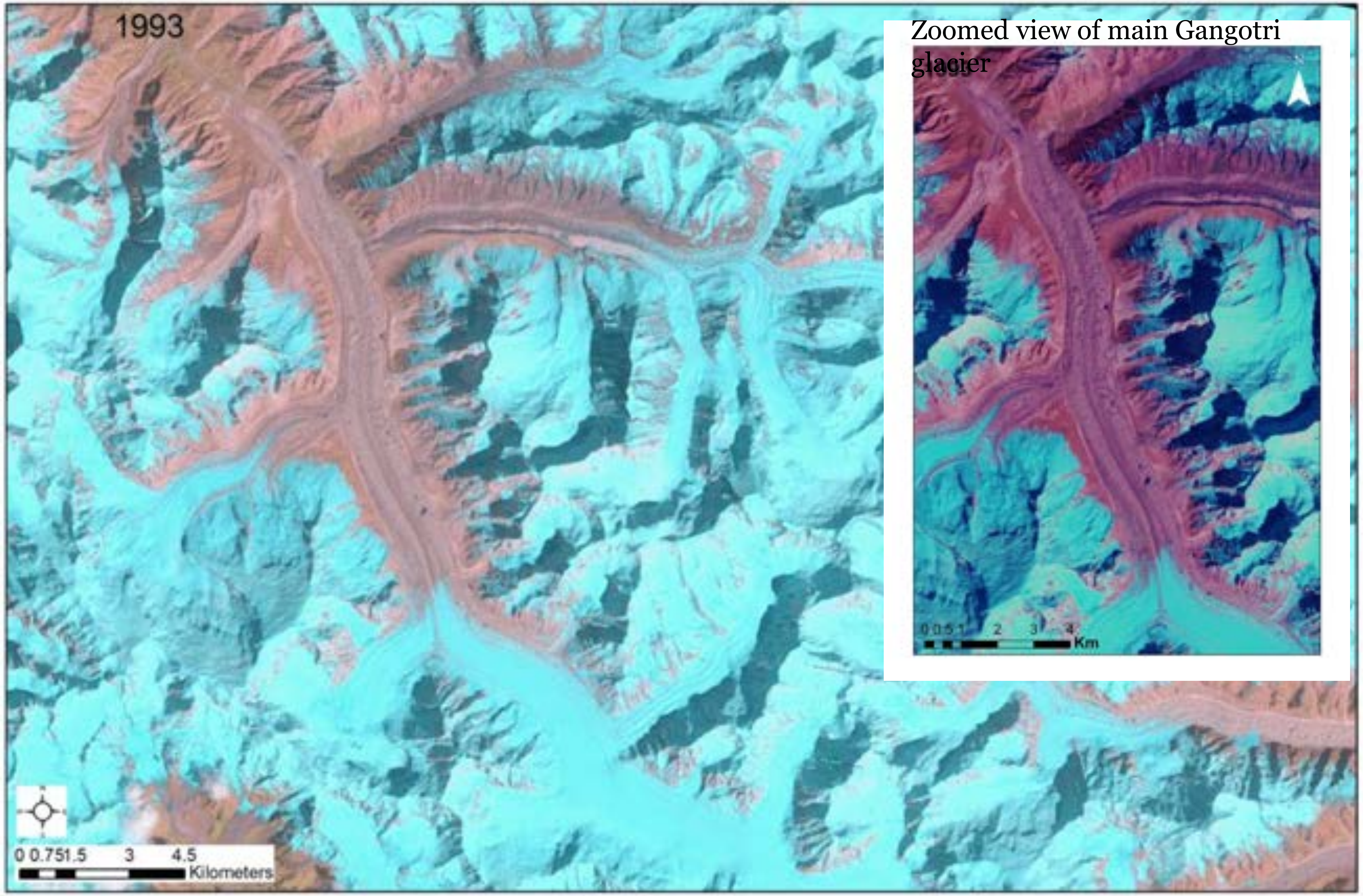
https://bhoonidhi.nrsc.gov.in/bhoonidhi/home.html

https://vedas.sac.gov.in/snow-cover/index.html

Head Water Reaches of Ganga River: Glaciers/snow as seen in multi-spectral satellite data



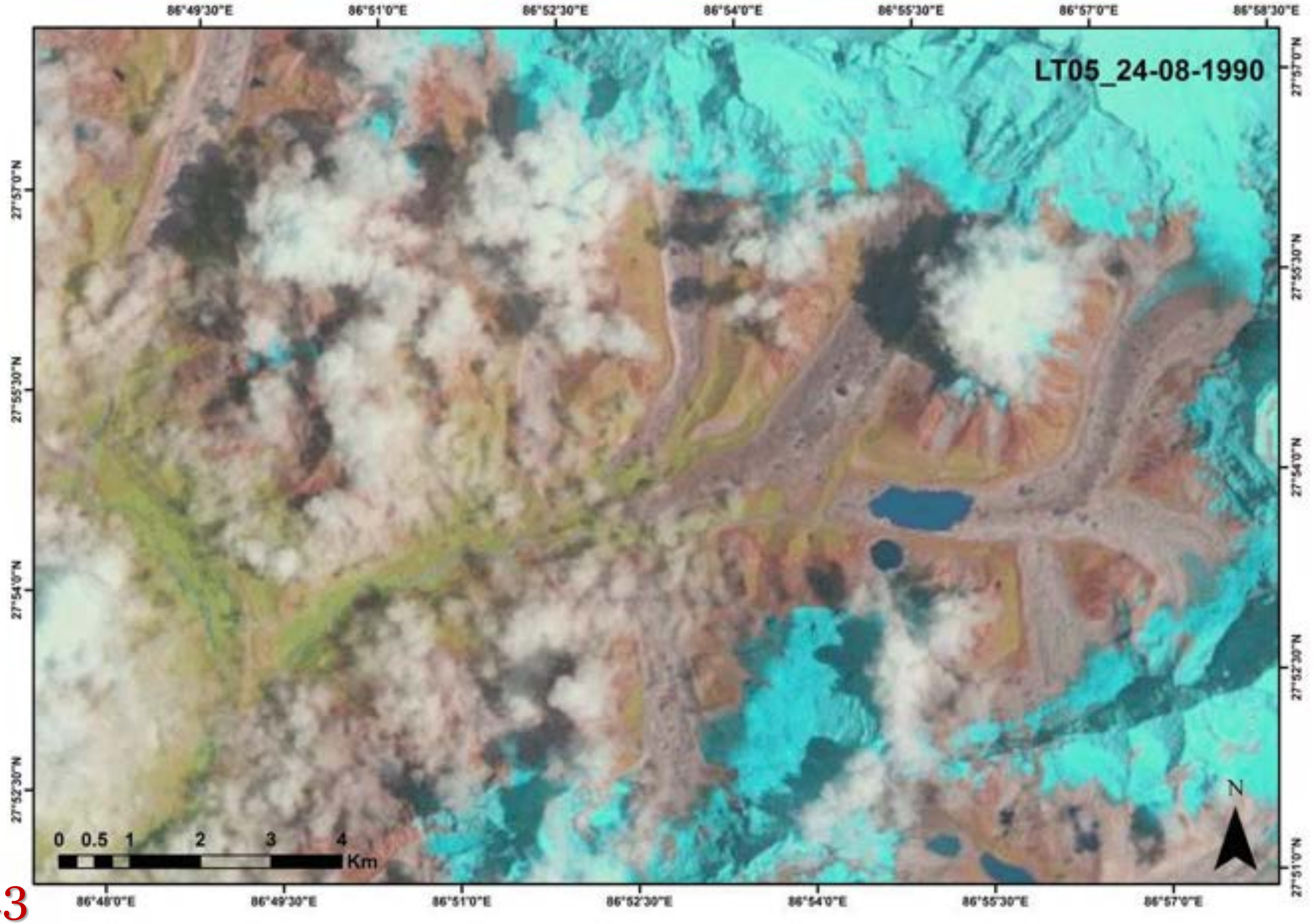
Gangotri group of glaciers, Bhagirathi basin, Uttarakhand



Total Retreat of Gomukh Snout from 1993 to 2019
415 m (15.96 m/year)

Mean surface velocity of main Trunk glacier for year 2014
20.83 m/year

Imja group of glaciers, Dudh Kosi basin, East Nepal, increasing GLOF risk



Total increase of glacier lake Length and area since 1990

Length: 1.08 Km.

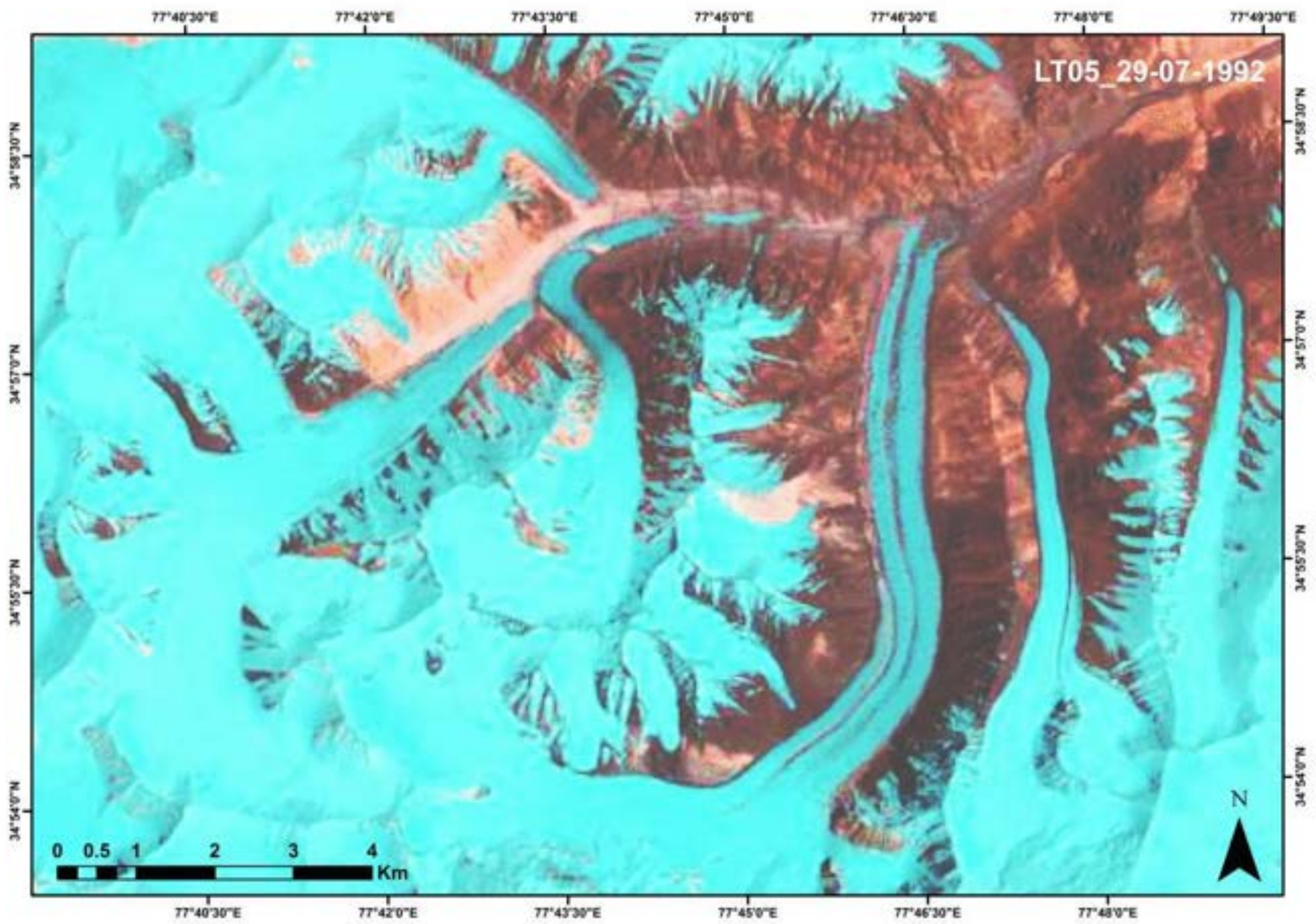
Area: 0.84 km²

Mean surface velocity of glacier for year 2017

23.15 m/year

Since 1960, a supra glacier lakes combined to form big single lake and has increased to 2.5km in length & Area of 1.44 km² and 150 metres deep. Increased GLOF risk due to such glacier lakes in Himalaya

Surging glacier of Karakoram, Indus river basin, J & K



Maximum Surge value (Km.)

1: 1.36 (2010-2011)

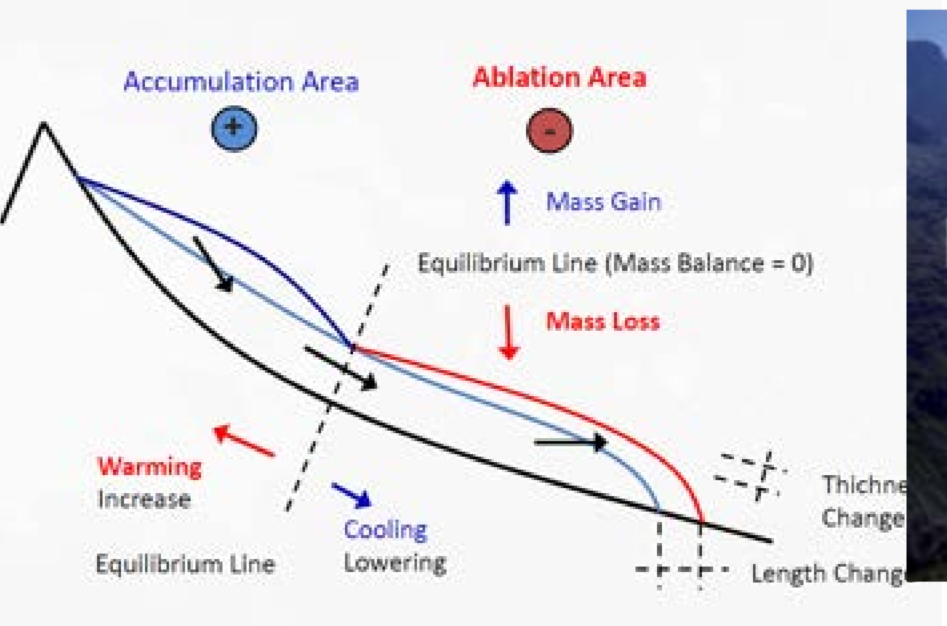
Total Surge value since 1991

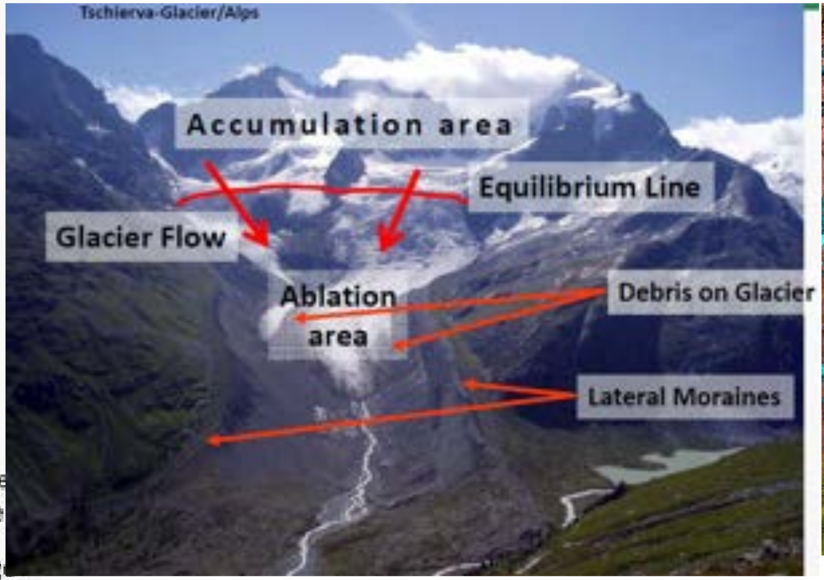
1: 2.76 Km.

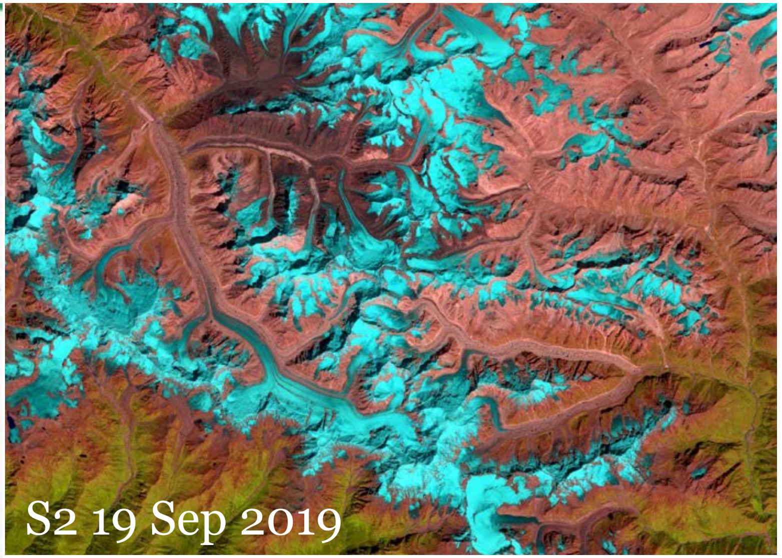
Mean surface velocity

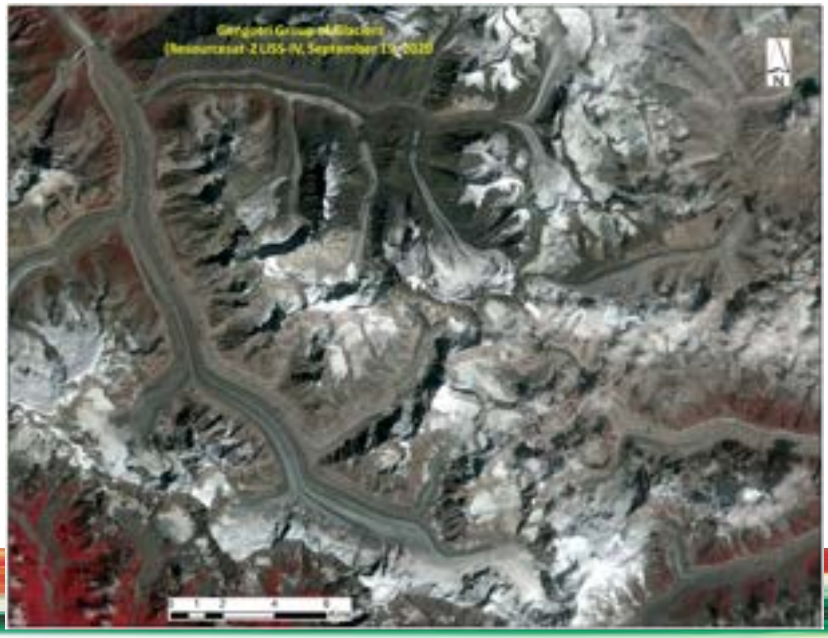
1: 39.57 m/year (2014)

Issues in Glacier Monitoring with optical Remote Sensing



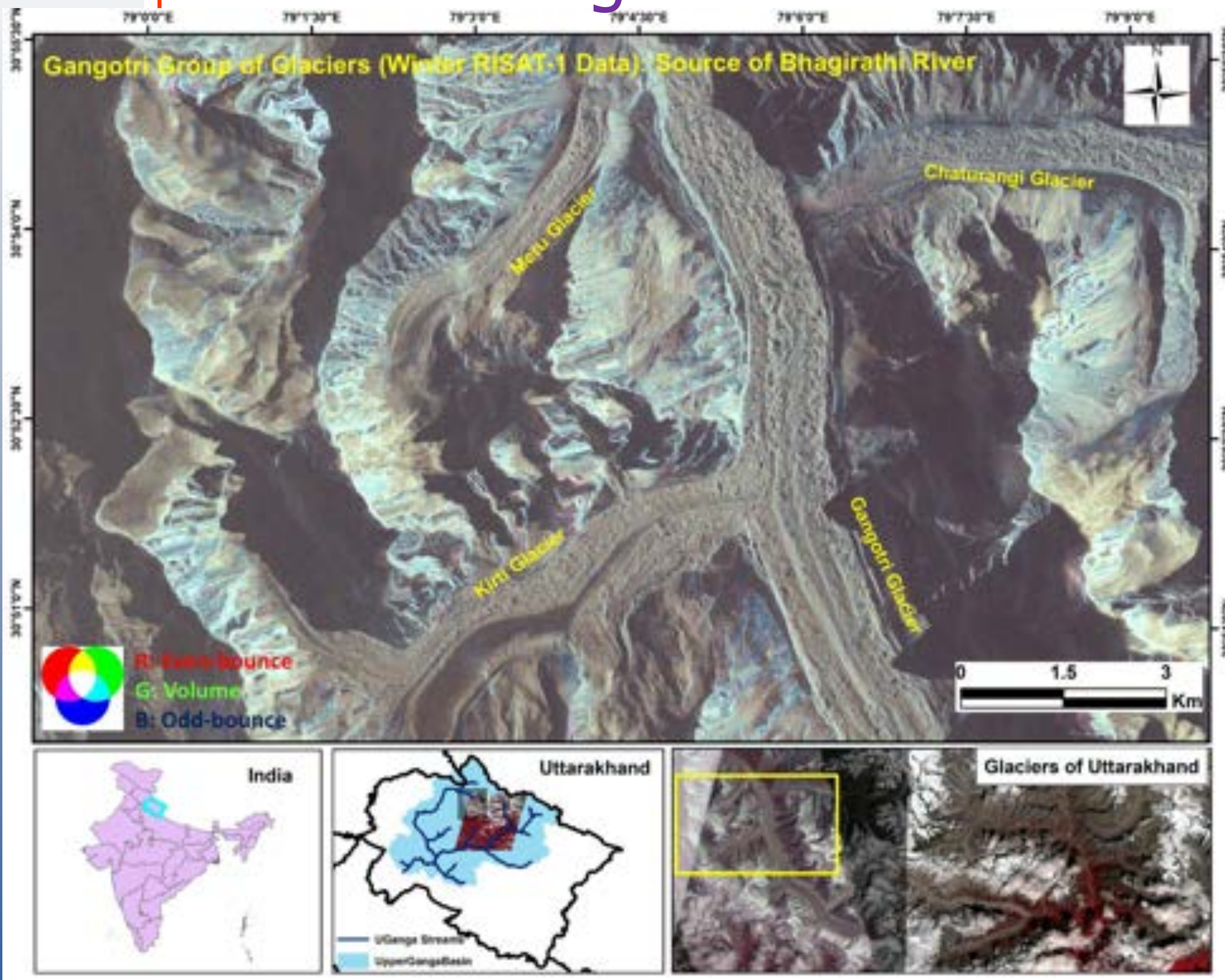


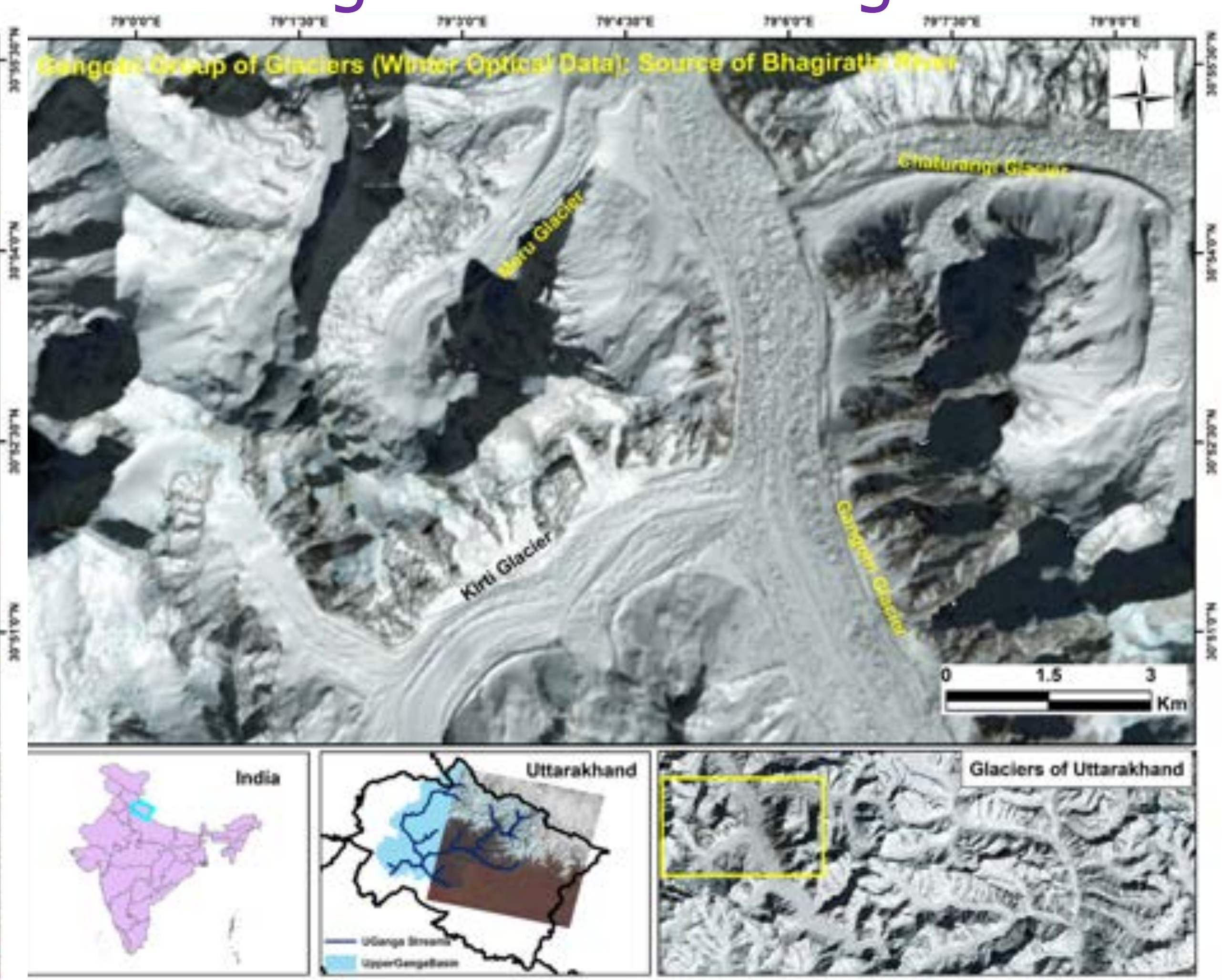




Source: Tobias Bolch, TUDresden, Universität Zürich

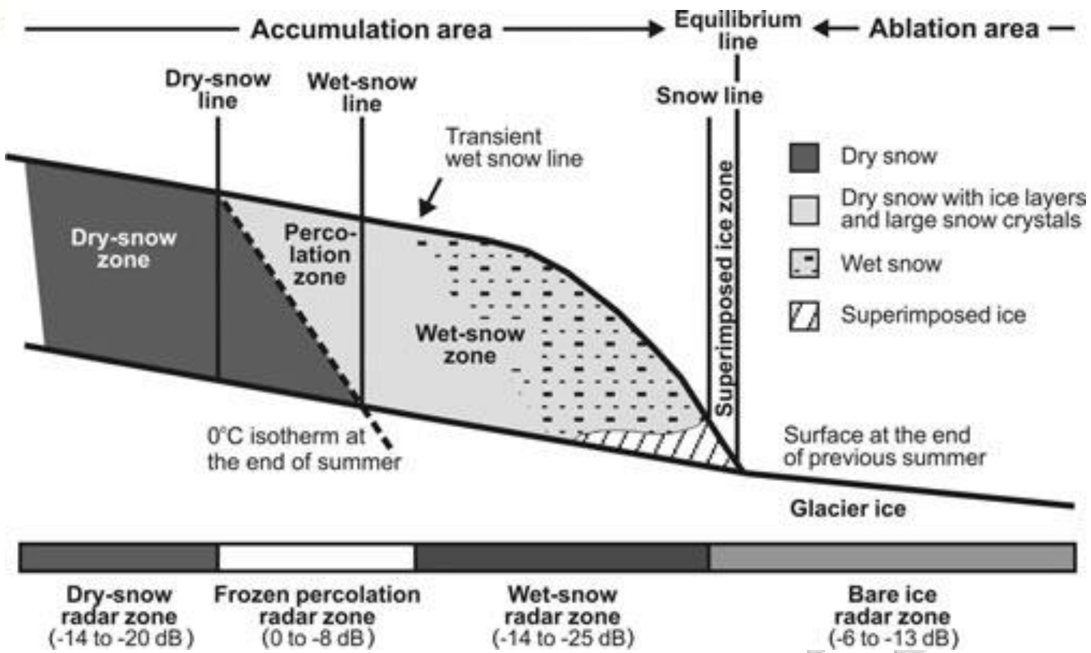
Advantages of SAR data for snow and glacier monitoring..





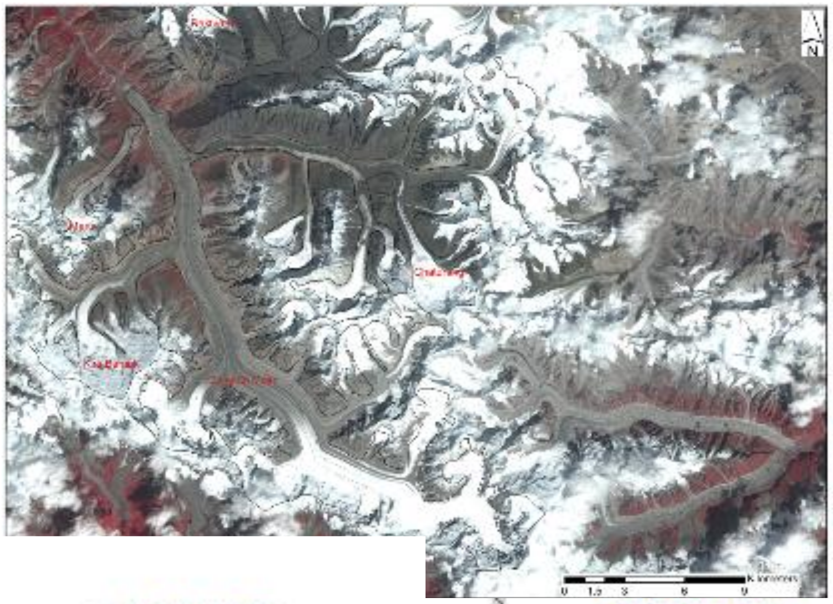
The above image shows the Gangotri Glacier and surrounding terrain in RISAT-1 FRS-2 and optical image of Landsat-8 dated February 18, 2014. Note that entire image is covered with deep snow and only few unique surface features are visible. This shows the importance of SAR data for continuous all weather, day-night monitoring of such glaciated regions

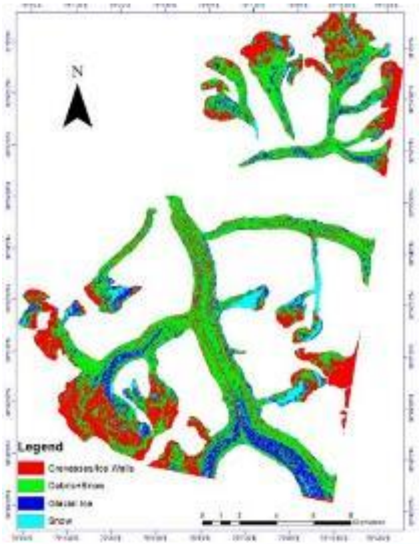
GLACIER FACIES CLASSIFICATION USING SAR DATA



Glacier zones as seen in SAR data

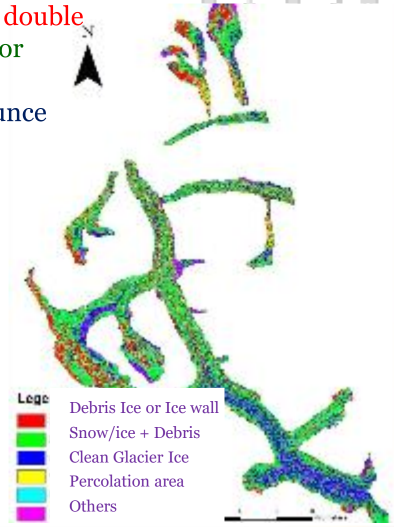
Gangotri glacier as seen in LISS-4 MX on 20 Sep 2012



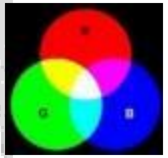


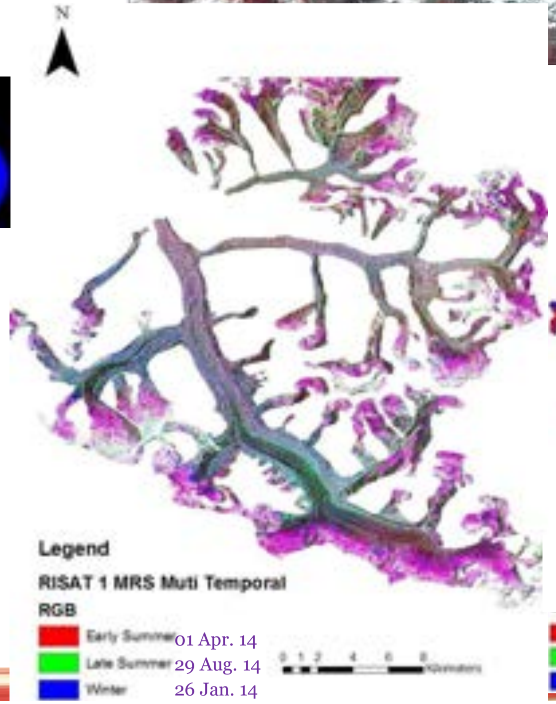
Radarsat-2 based classification

R: Even or double
G: Diffuse or Round
B: Odd bounce

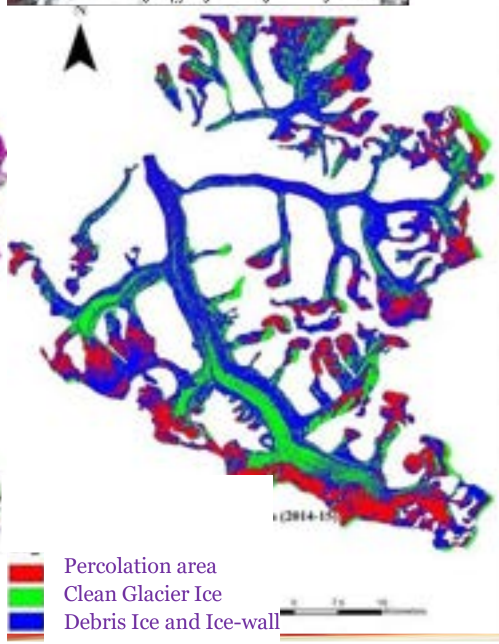


Glacier classes using RISAT-1 hybrid data
18 Feb 2014 FRS-1 Hb





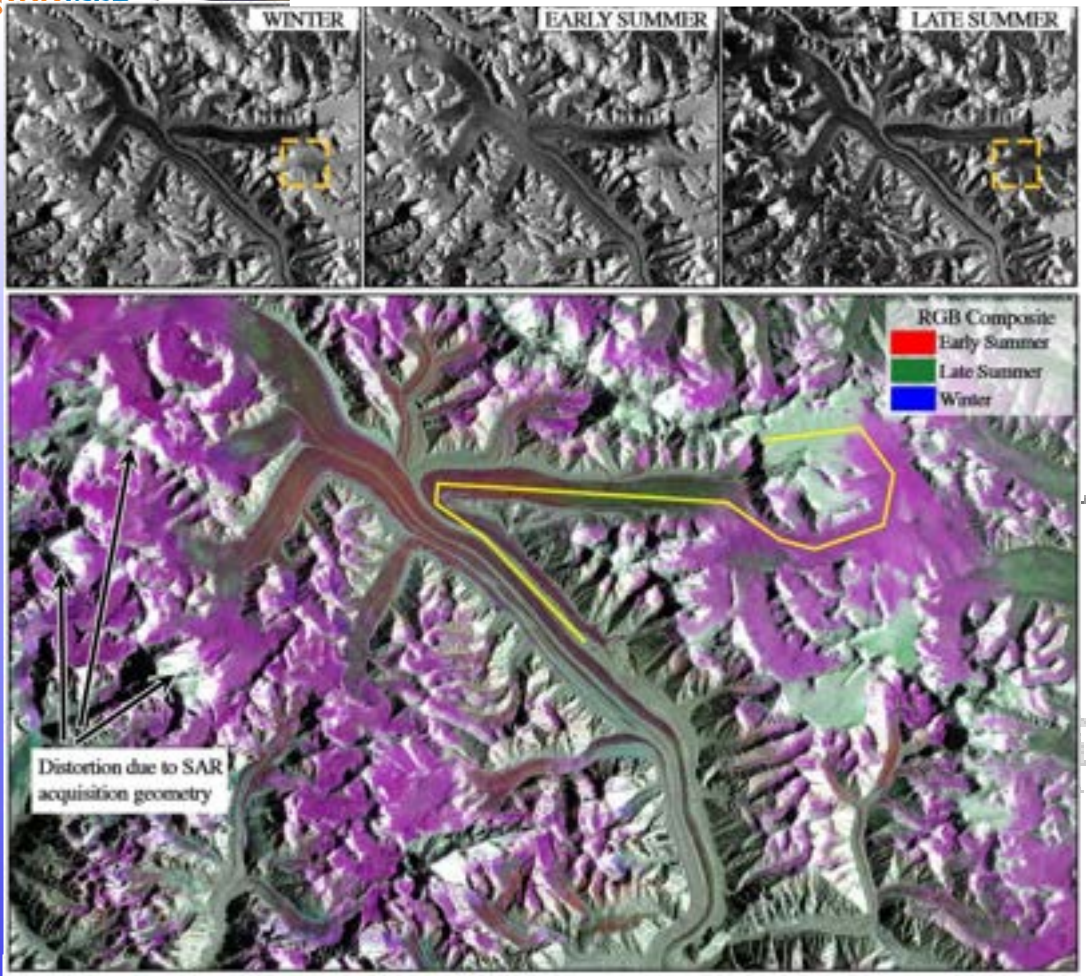
RGB of RISAT-MRS temporal data

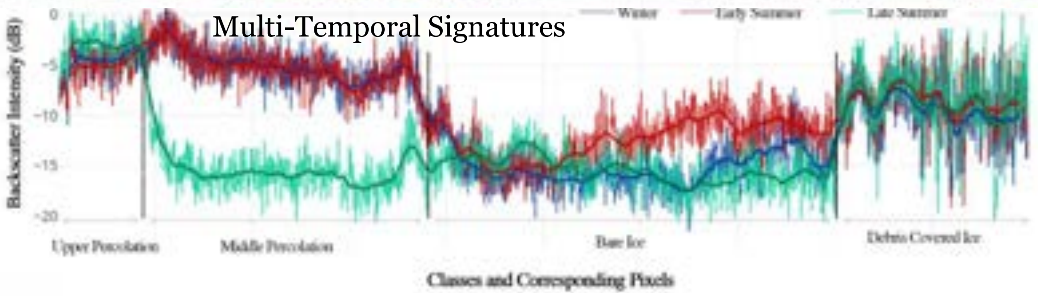


Glacier classes using MRS composite data

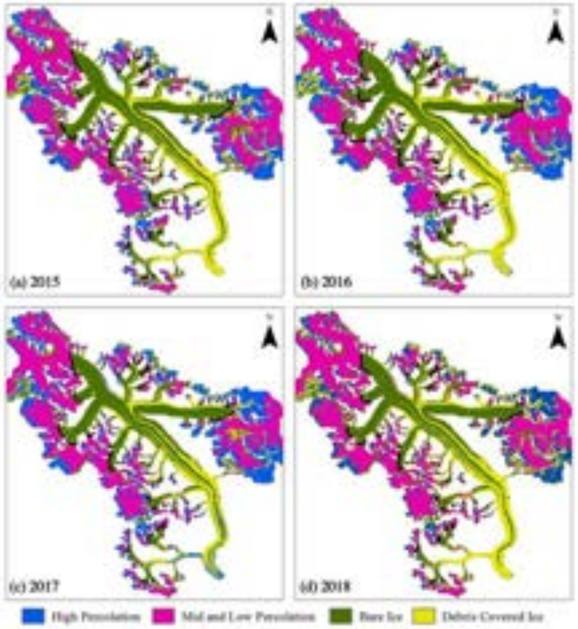
Thakur et al., 2023, Gangotri glacier dynamics from multi-sensor SAR and optical data,https://doi.org/10.1016/j.asr.2023.03.001

Glacier radar zones & ELA mapping using time series of SAR data

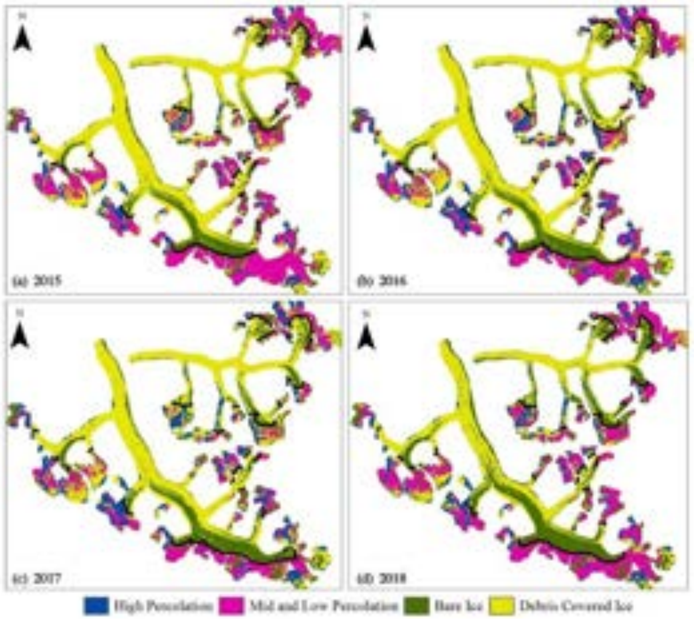


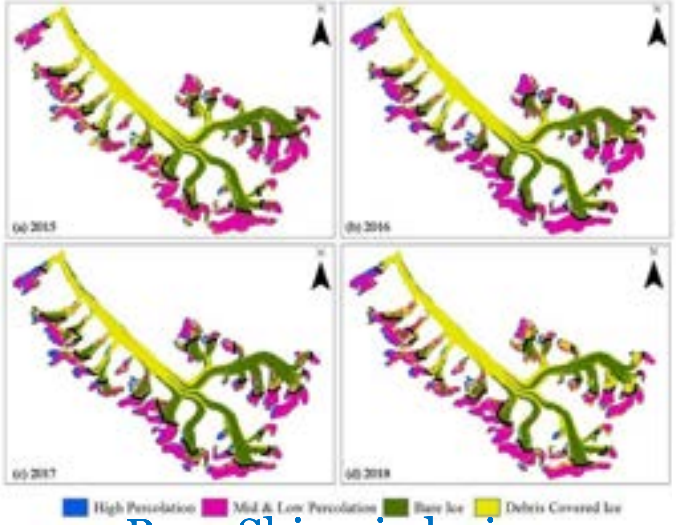


Siachen Glacier



Gangotri Glacier





Bara Shigari glacier

Assessment Year	Equilibrium Line Altitude (ELA) (m.a.s.l.)		
	Siachen Glacier	Bara Shigri Glacier	Gangotri Glacier
2015	5157±1.5*	5375±2.1*	5133±3.2*
2016	5185±0.7†	5397±0.6	5232±3.0
2017	5172±1.9	5407±3.3	5383±2.7†
2018	5176±1.1	5409±1.2†	5299±4.1

*Lowest and †Highest ELA during the study period

Glacier radar zones are used for further estimating the ELA of 3 major glaciers of NWH

NISAR time series and QP data would further improve such estimates of ELA/SLA

Siachen Glacier, Karakoram Himalayas

Mahagaonkar et al., 2019

SAR DATA (DINSAR) BASED GLACIER VELOCITY METHODOLOGY

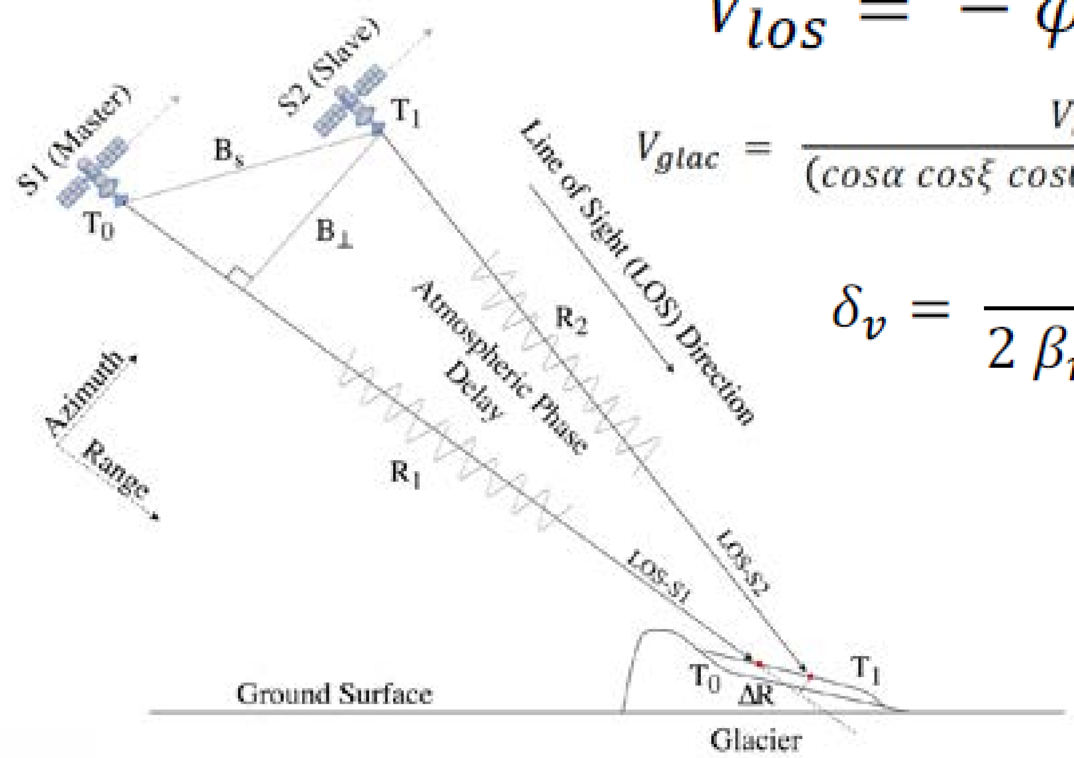
$$\Delta\varphi = W\,(\Delta\varphi_{\text{flat earth}} + \Delta\varphi_{\text{topography}} + \Delta\varphi_{\text{displacement}} + \Delta\varphi_{\text{atmosphere}} + \Delta\varphi_{\text{noise}})$$

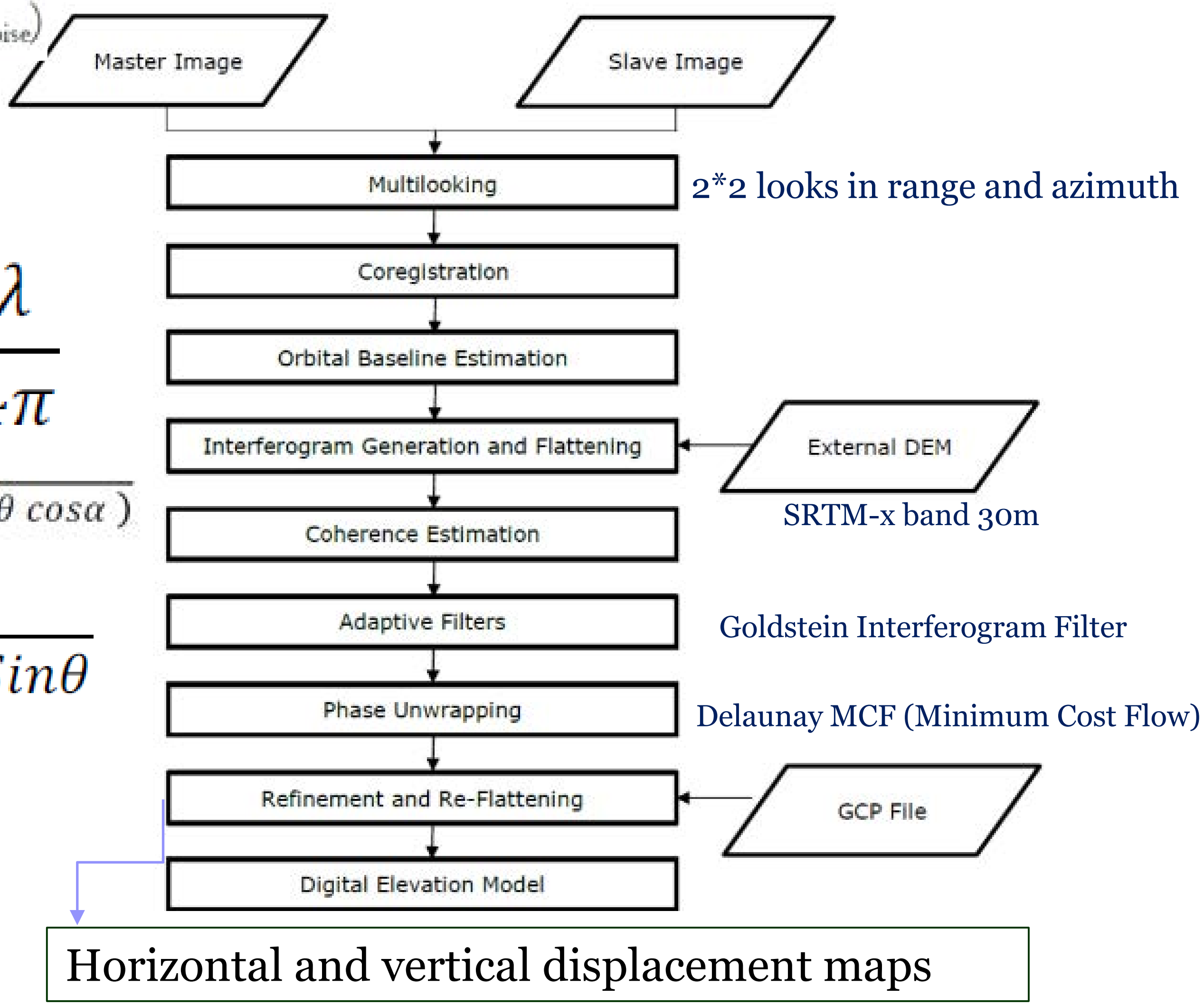
$$\Delta\varphi = -\frac{4\pi}{\lambda}\,\frac{B_{\perp}h}{R_1\,Sin\theta} + \frac{4\pi}{\lambda}d + \Delta\varphi_{noise}$$

$$V_{los} = -\,\varphi_{uw}\,\frac{\lambda}{4\pi}$$

$$V_{glac} = \frac{V_{los}}{(cos\alpha\;cos\xi\;cos\theta\;-\;sin\theta\;cos\alpha\,)}$$

$$\delta_v = \frac{\lambda}{2\,\beta_r\,\Delta T\,Sin\theta}$$



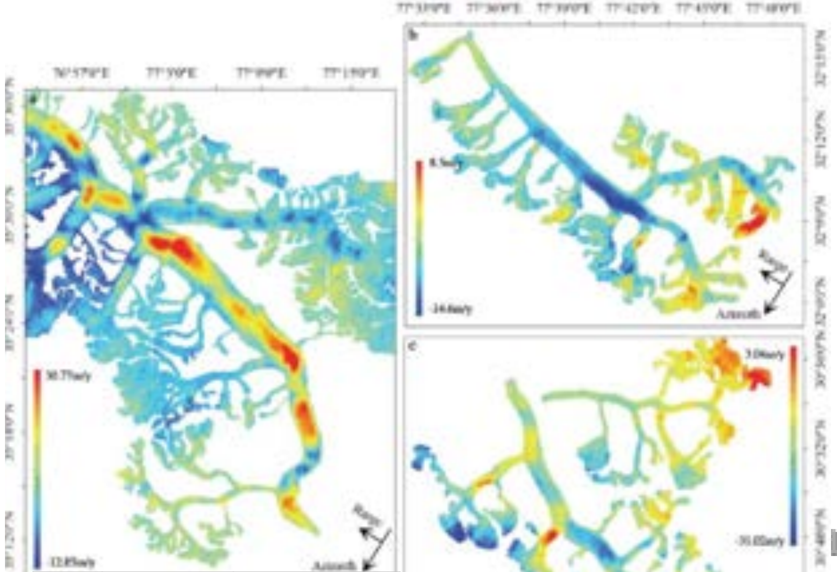


Glacier velocity estimation using DInSAR and offset/feature tracking methods

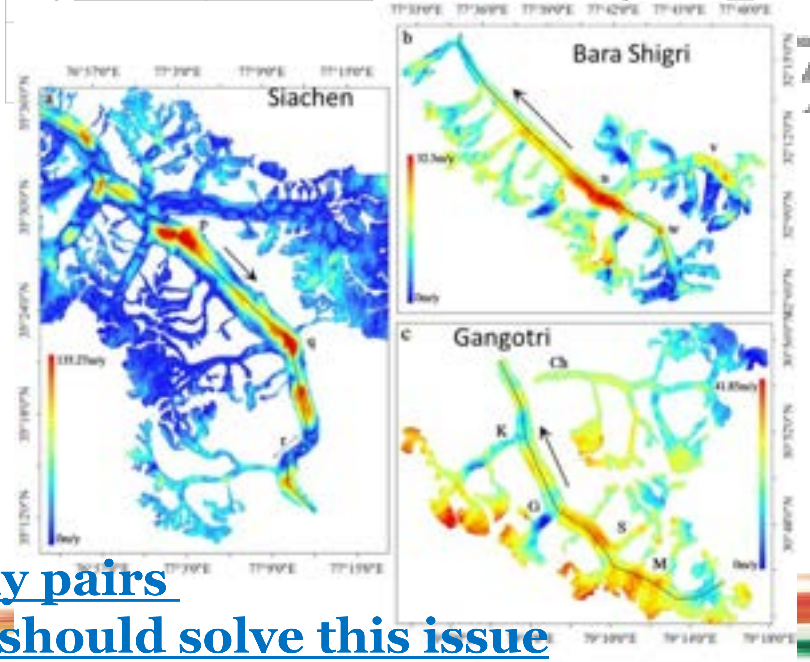
Practical issue of converting single direction (Asc or Desc) LoS velocity data to 2D horizontal velocity, as the big mountain compound glaciers have variable main ice flow directions

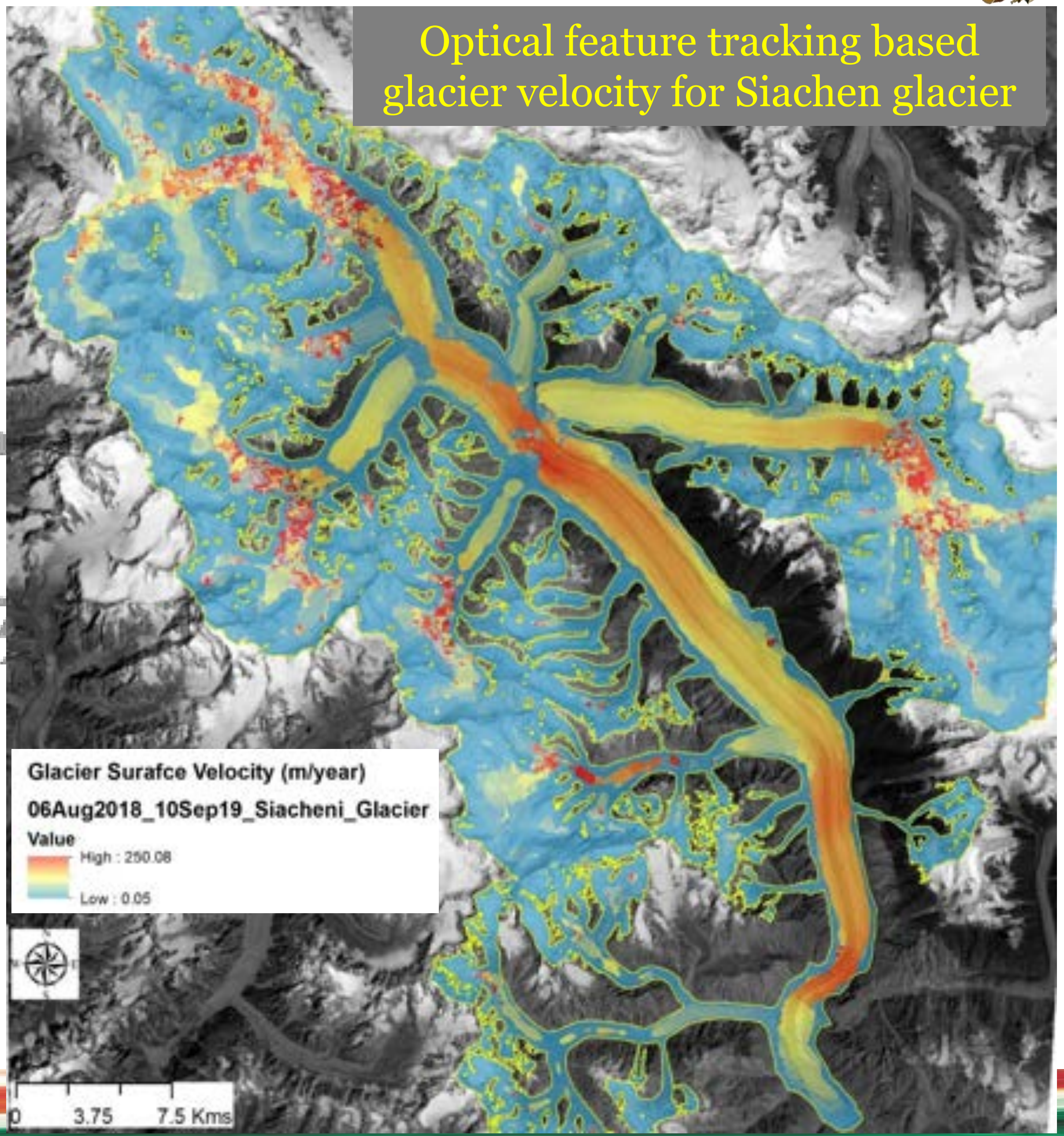
$$V_{hor} = V_{LoS}/(\cos\omega \cos\xi \cos\theta - \sin\theta \cos\omega) .$$

Where, V_{hor} is the actual surface velocity in flow direction, V_{LoS} is the the velocity in LoS direction and ω, ξ, θ are the slope, aspect angle with respect to radar direction and look angle respectively.



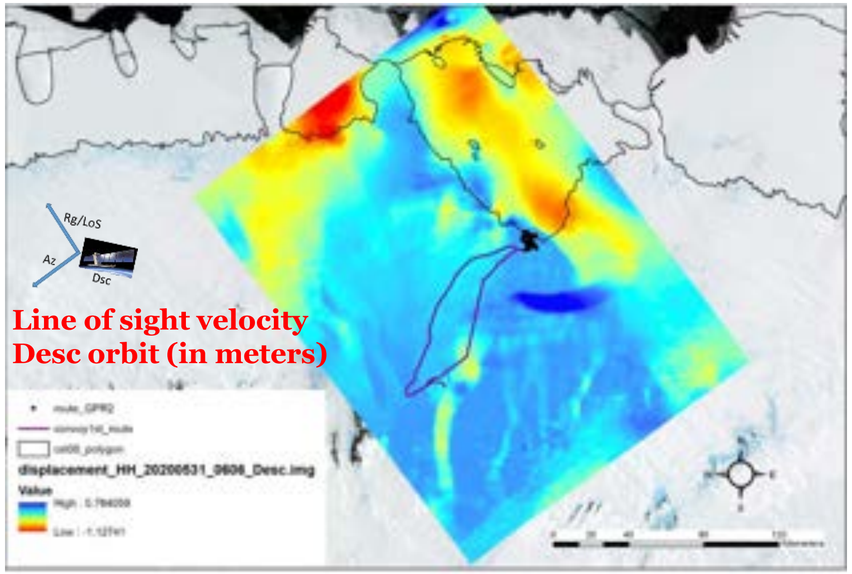
Glacier	Point/Region	Estimated Velocity (m/y)
Siachen Glacier	'p'	135.27±3.9
	Between 'p' and 'q'	83.2±10 (60.0 – 100.0)
	'r'	5.0 – 20.0
Bara Shigri	'u'	32.5±1.6 (27.0 – 32.0)

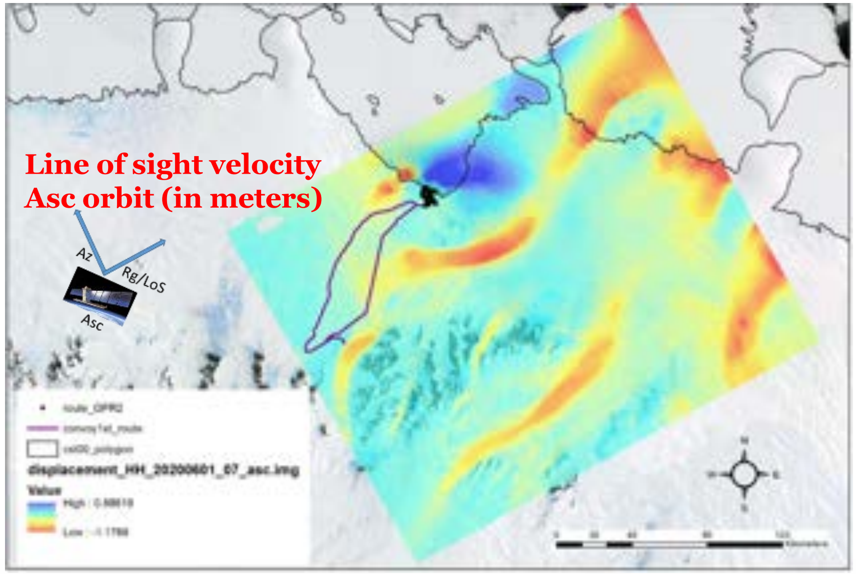


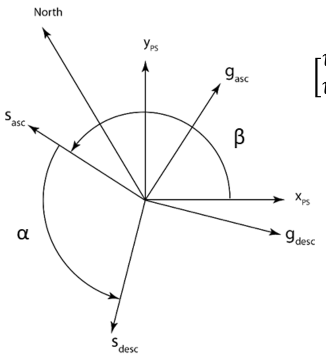


NISAR 12 day pairs in Asc/Desc should solve this issue

2D-Glacier Velocity estimation using DInSAR based methods using Sentinel-1, 6 day InSAR data; Same algorithm being used for NISAR





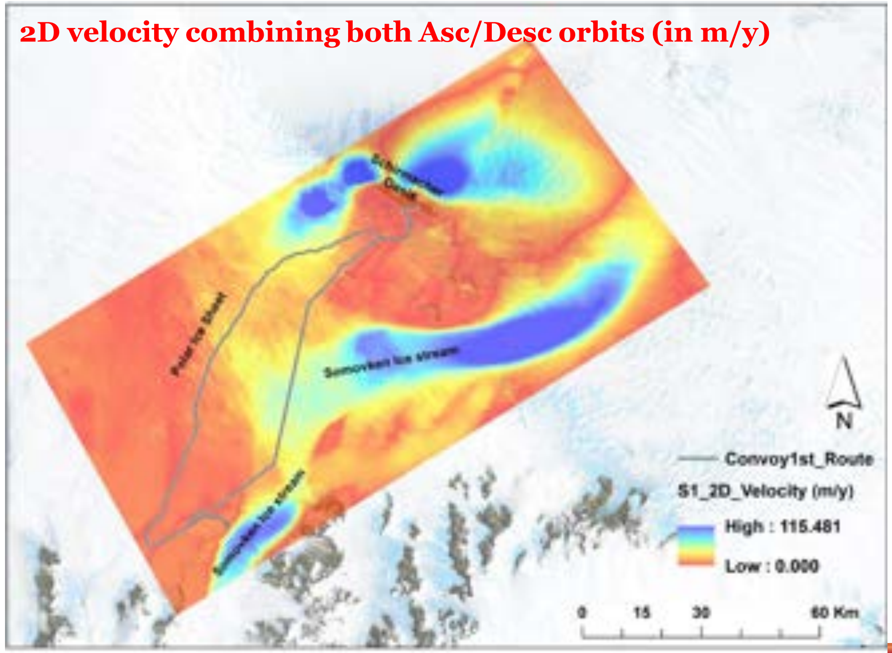


$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = (\boldsymbol{I} - \boldsymbol{ABC})^{-1} \begin{bmatrix} \dfrac{\lambda_a \tilde{\Phi}_a}{4\pi \Delta T_a \sin(\psi_a)} \\ \dfrac{\lambda_d \tilde{\Phi}_d}{4\pi \Delta T_d \sin(\psi_d)} \end{bmatrix}$$

$$\boldsymbol{A} = \begin{bmatrix} \cos\beta & \cos(\alpha+\beta) \\ \sin\beta & \sin(\alpha+\beta) \end{bmatrix}$$

$$\mathbf{C} = \begin{bmatrix} \dfrac{\partial z}{\partial x}\cot(\psi_a) & \dfrac{\partial z}{\partial y}\cot(\psi_a) \\ \dfrac{\partial z}{\partial x}\cot(\psi_d) & \dfrac{\partial z}{\partial y}\cot(\psi_d) \end{bmatrix}$$

NISAR ATBD Implemented with S-1 InSAR data in Asc/Desc Mode datasets For cDML region of EAIS



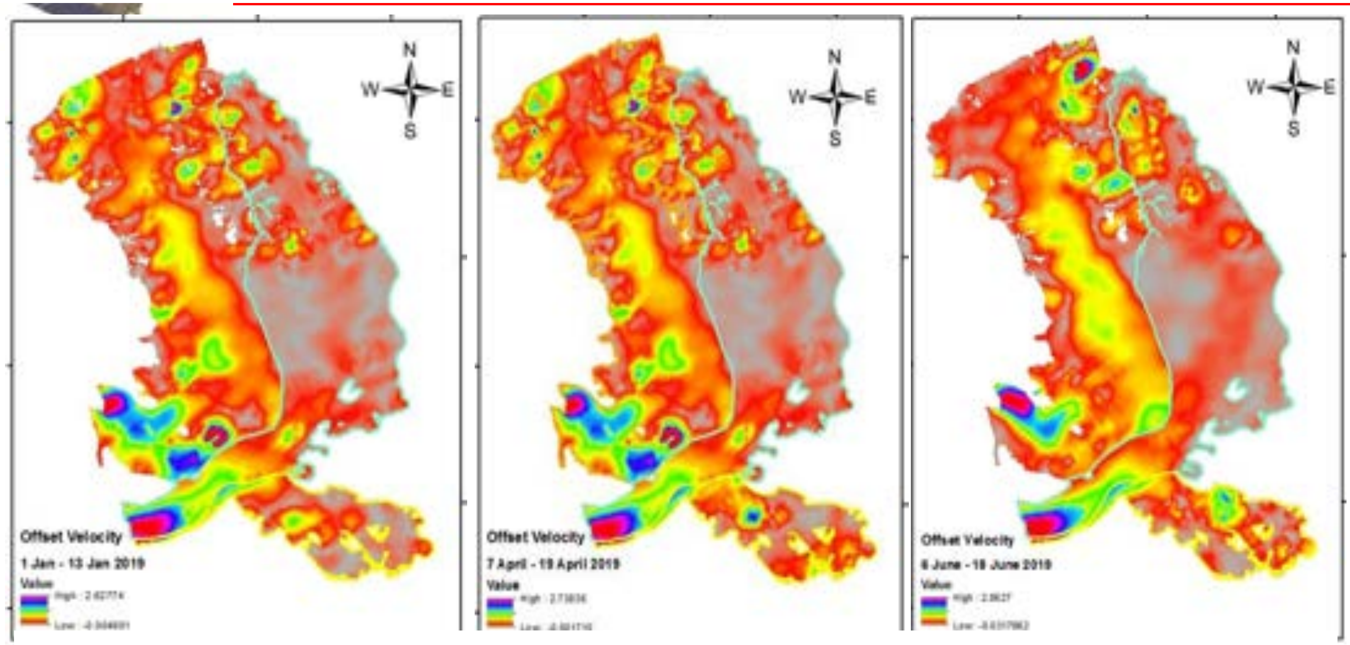
This velocity is used for estimating influx and outflux, which comes in range of 0.18–4.167 Gt/y and 0.201 to 1.278 Gt/y respectively for selected ice streams, indicating net positive mass balance for the selected area.

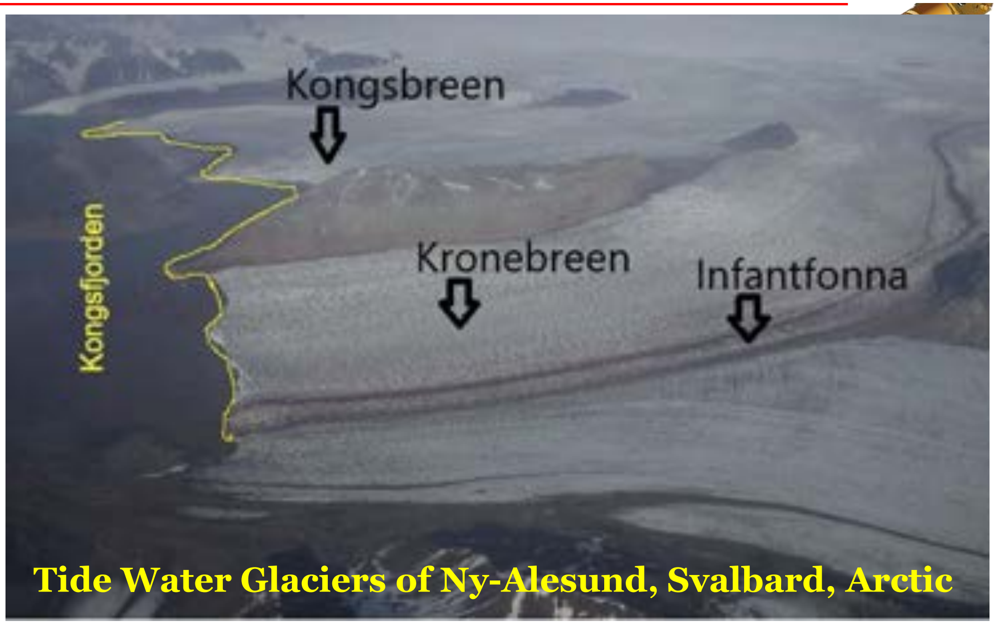
Praveen K. Thakur, et al., Polar Science, (2021). https://doi.org/10.1016/j.polar.2021.100737

SAR based Glacier Velocity & Radar Zone Classification for selected areas in Svalbard, Arctic

Sentinel-1 SAR data based results

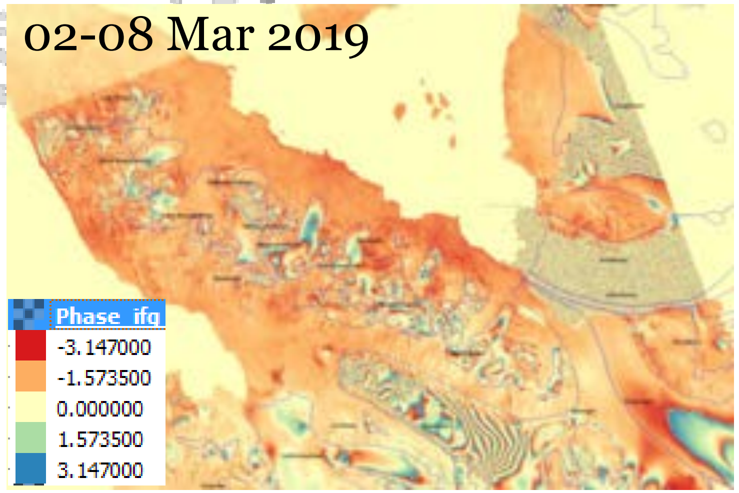
Better Results expected from 12 day interval NISAR data

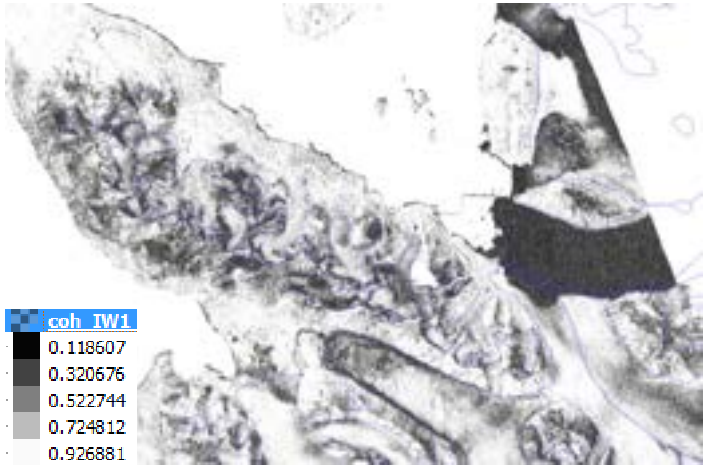




Seasonal glacier velocity estimation of 2019 season using offset tracking

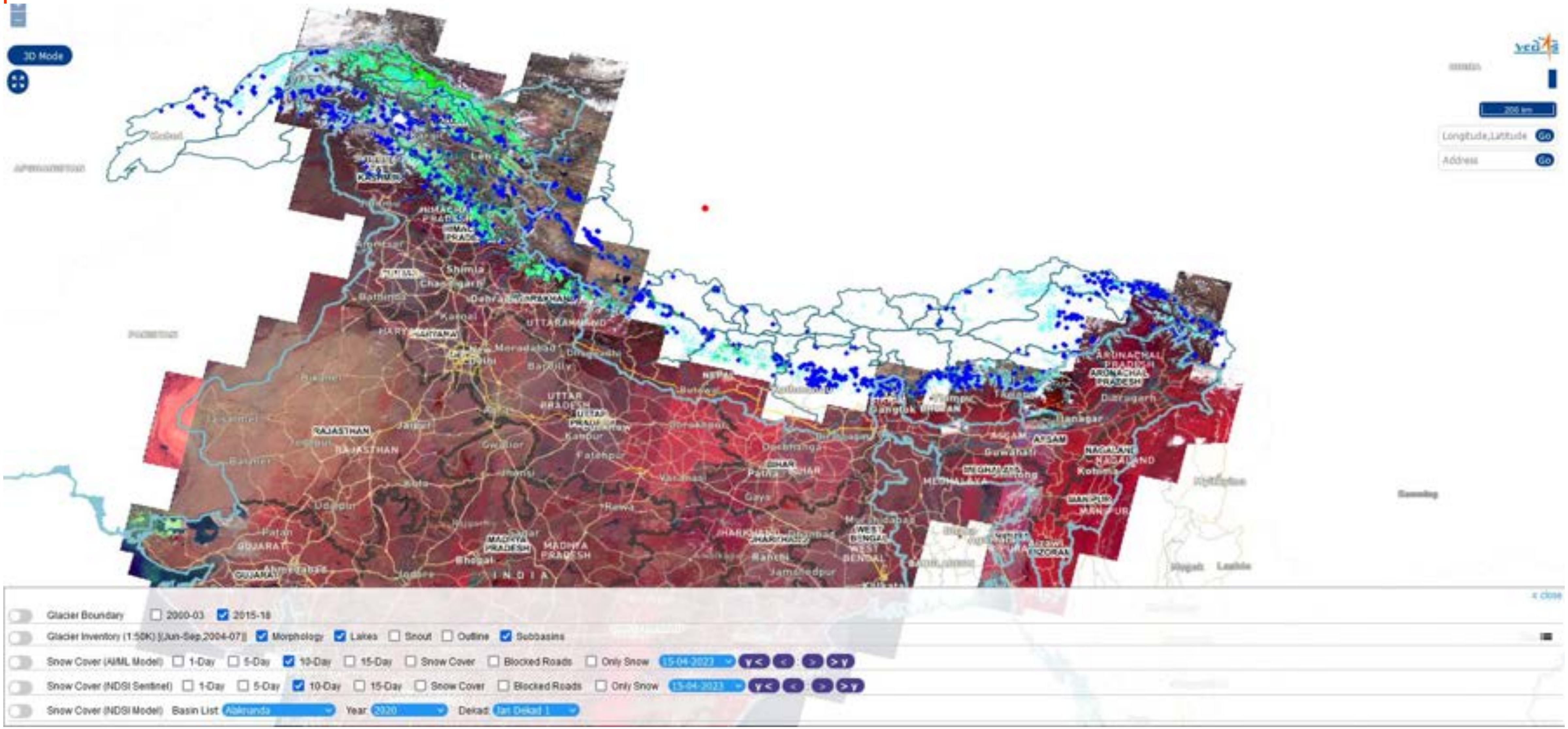
Date and year	Max Velocity (m/day)
04 Feb 2017- 16 Feb 2017	2.72
29 April 2017 - 11 May 2017	2.77
08 Sept 2017- 20 Sept 2017	2.36
06 Jan 2018 - 18 Jan 2018	2.57
12 April 2018 - 24 April 2018	2.6
03 Sept 2018 - 15 Sept 2018	2.45
01 Jan 2019 - 13 Jan 2019	2.62
07 April 2019 - 19 April 2019	2.7
06 June 2019 - 18 June 2019	2.86





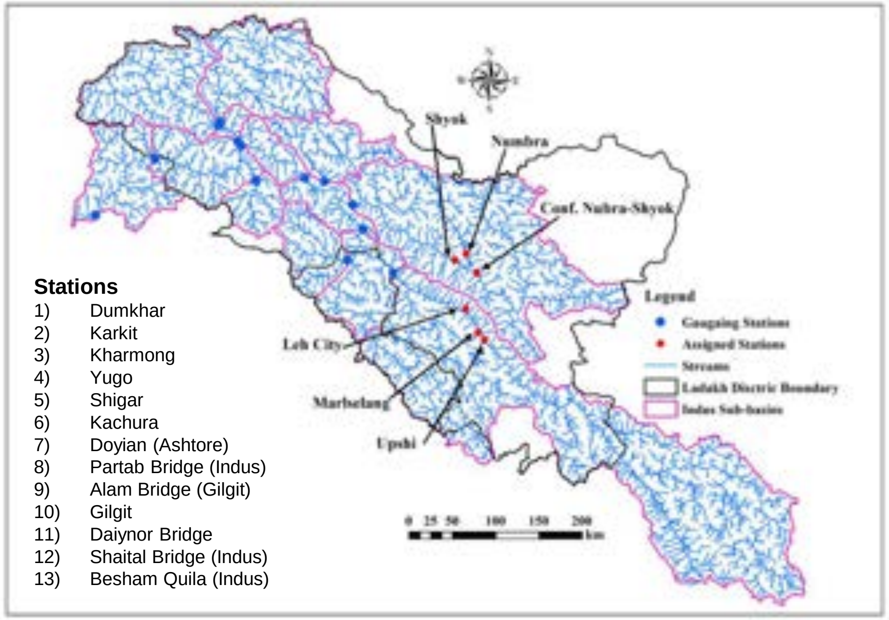
DInSAR works only for slow moving glaciers, & fast moving frontal parts of tide water glaciers are studied using SAR based offset tracking methods

Glacier and Glacier lakes monitoring from Indian remote sensing data



https://vedas.sac.gov.in/snow-cover/index.html

Satellite derived snow cover, glacier area can be used with Glacio-hydrological models for Water Resources Availability Assessment: A case study of upper Indus basin

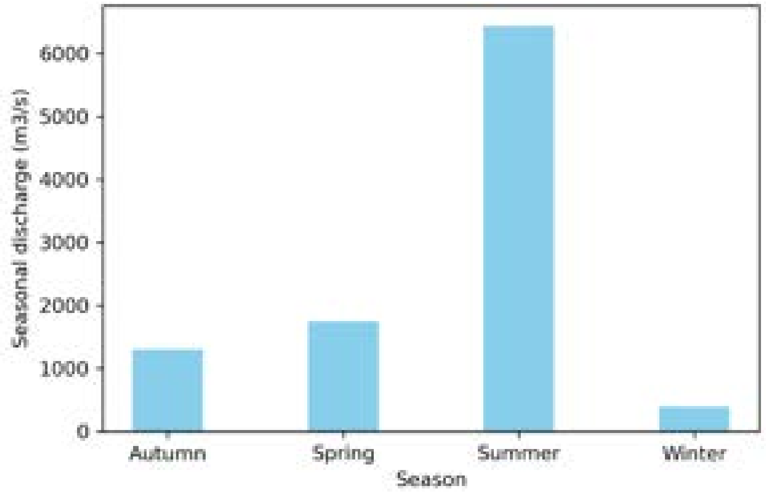


The snowmelt runoff contributes to the 69% of the total runoff, while the Glacier melt was observed to be 17% of the total runoff, the base flow contribution was 9% runoff and the rainfall runoff was observed to be the 5% of the total discharge as per long term simulations for Indus basin.

Long term monthly mean shows the average discharge of ~8000 cumecs is available at the Besham Quila station

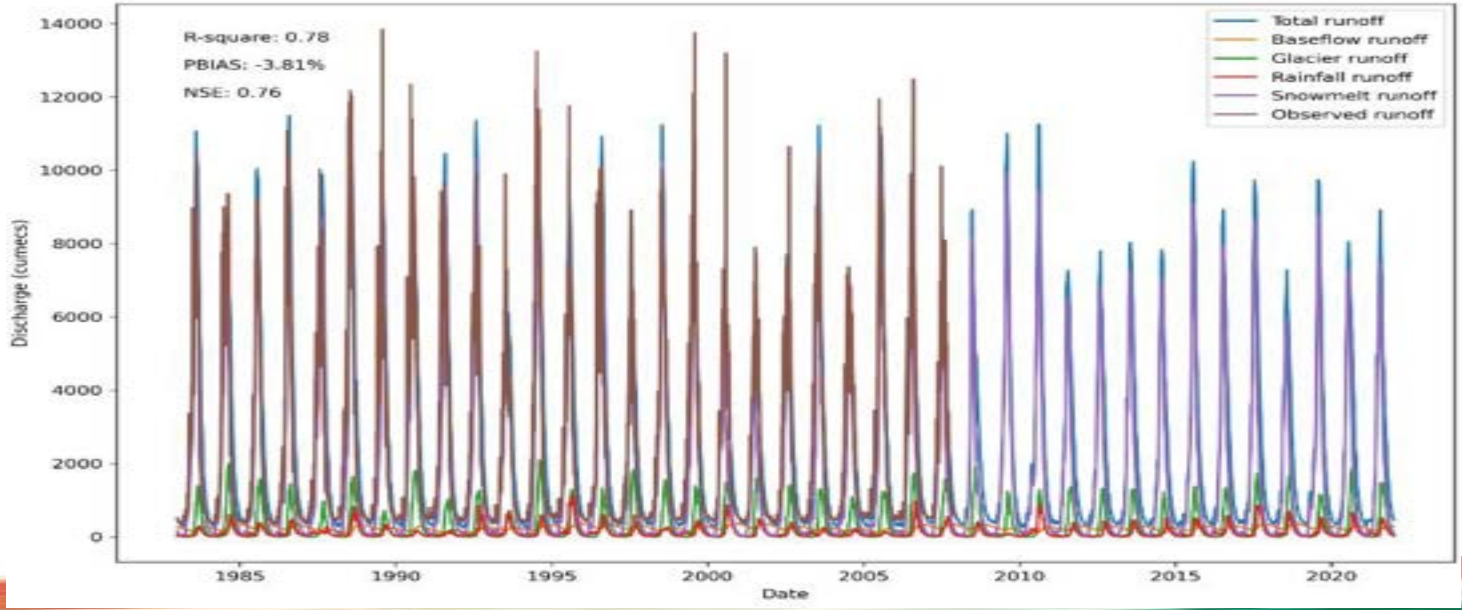
Model Performance

- ❖ **Daily** Discharge
  - ▪ **R^2 = 0.82**
  - ▪ **NSE = 0.80**
- ❖ **Monthly** Discharge
  - ▪ **R^2 = 0.92**
  - ▪ **NSE = 0.86**

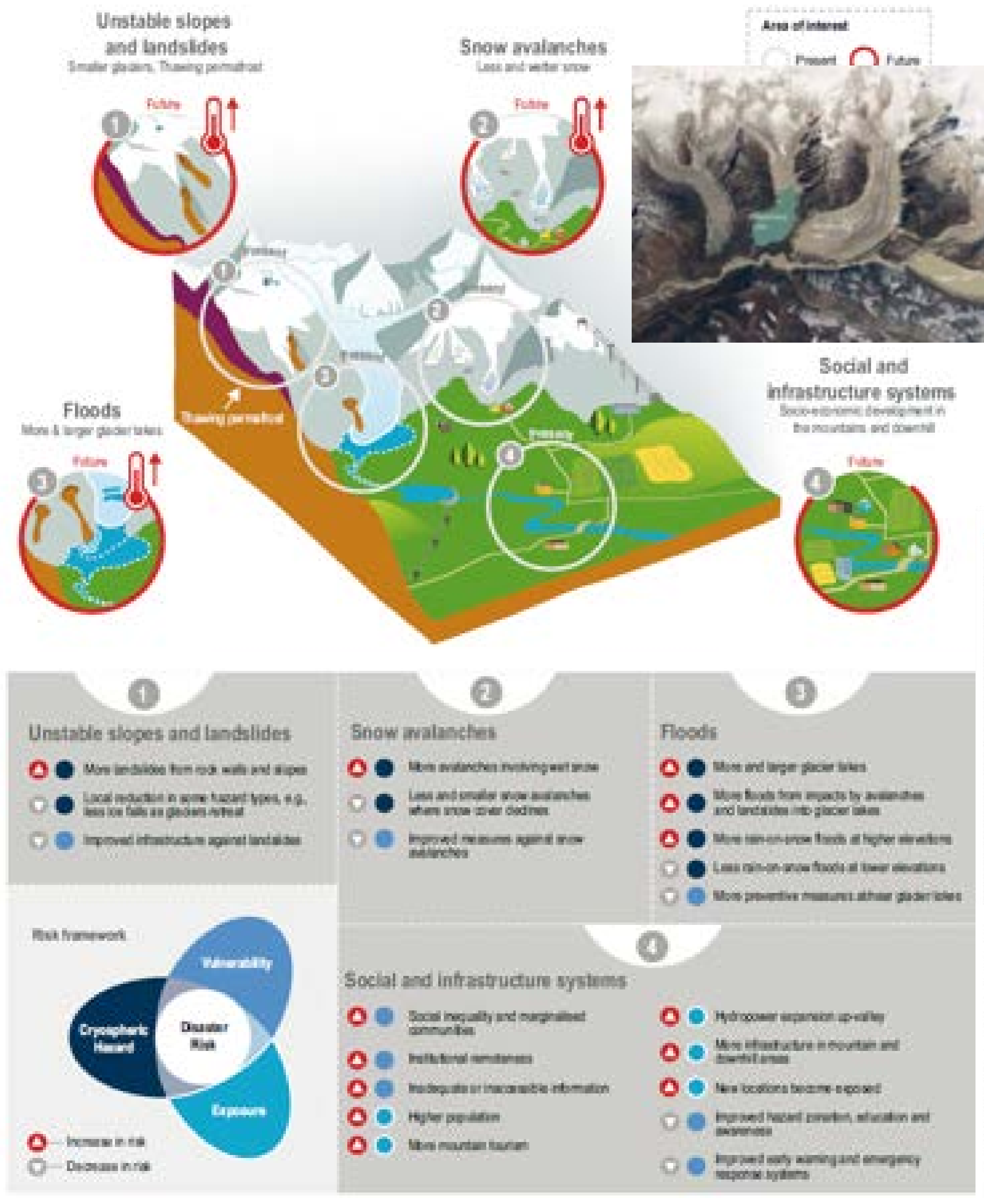


❖ **Discharge** Contributions

- Snowmelt (14-96%); Glacier melt (1-43%)

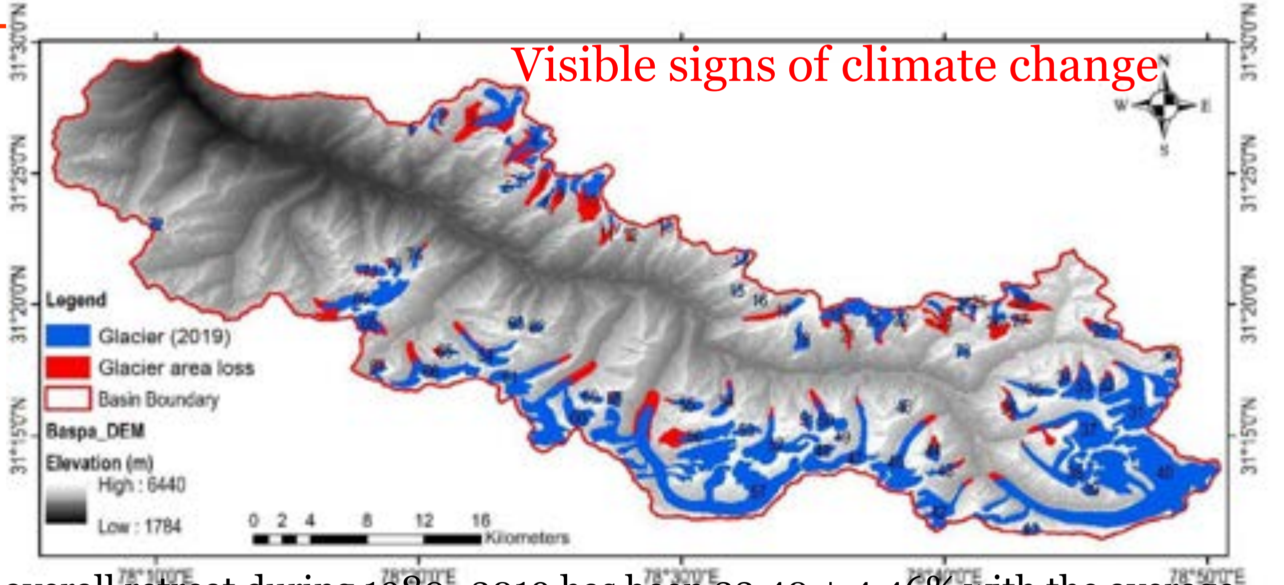


Anticipated Changes in future climate for Mountain
Few have already happened in the last 20 years !

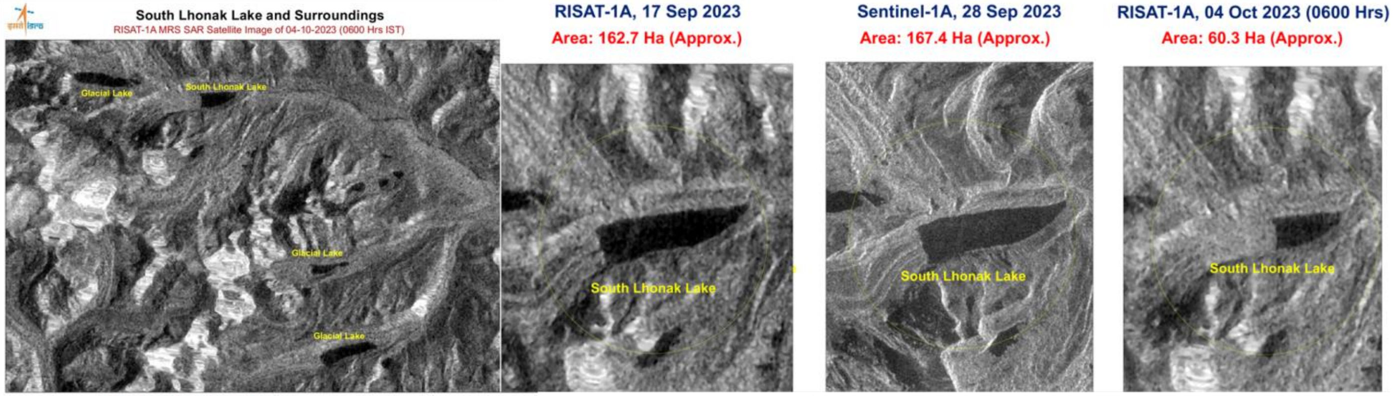


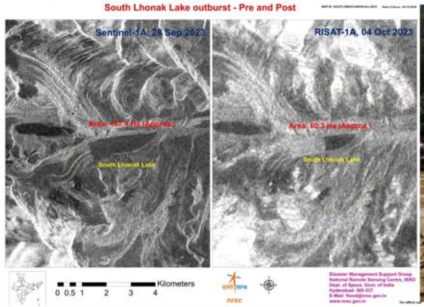
Source: IPCC

Visible signs of climate change



The overall retreat during 1980–2019 has been 22.40 ± 4.46% with the average loss in the area as 1.11 ± 0.01 km² a^{-1} in the entire Baspa basin. Singh et al., 2021



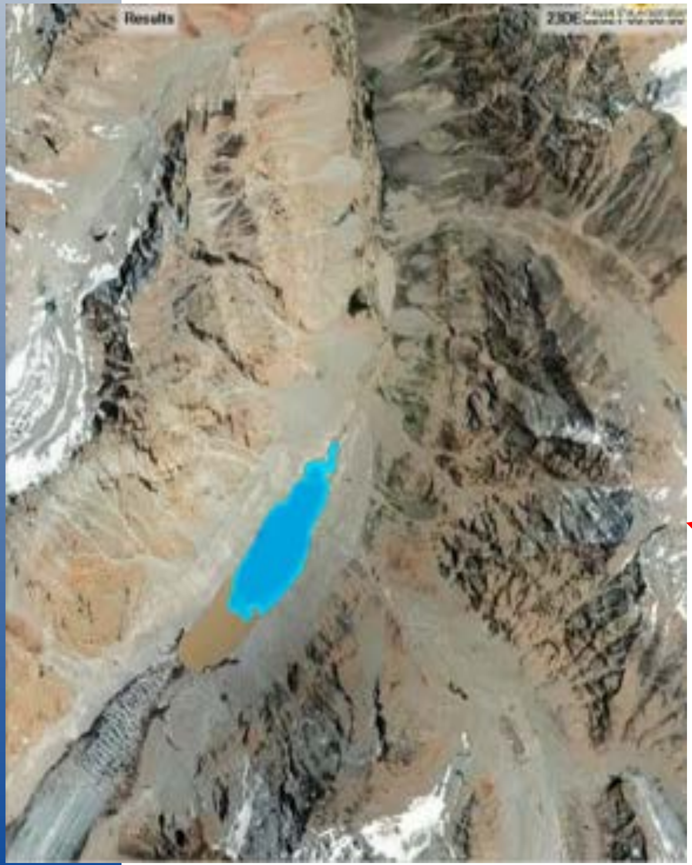


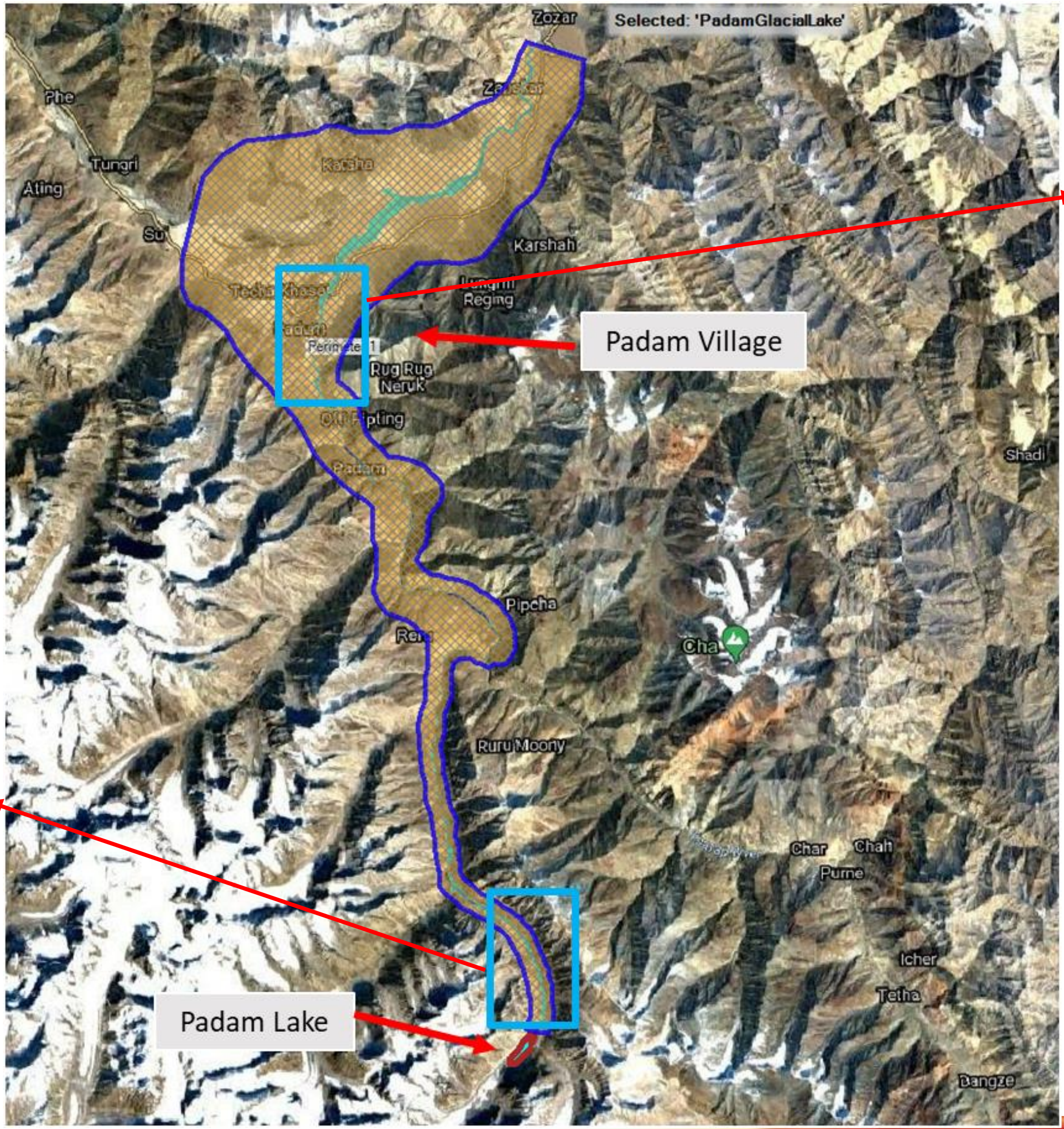
~107 Ha, reduction in lake water area post GLOF
~ 63% water drained during GLOF event

"The lake outburst in portions of Lhonak Lake in North Sikkim caused a rise in water levels with very high velocities near about 15m/sec, crossed the CWC (Centre Water Commission) Melli site measuring 227 m, near about 3m above Danger Level, at 0600 am," CWC 2023

Flood Hazard Assessment for GLOF: A must for mitigation of climate change

Lake Area: 0.58 km^2
Volume: 15.77 MCM
Mean Depth: 10 m
2h Breach Peak
Discharge: 2100 cumec

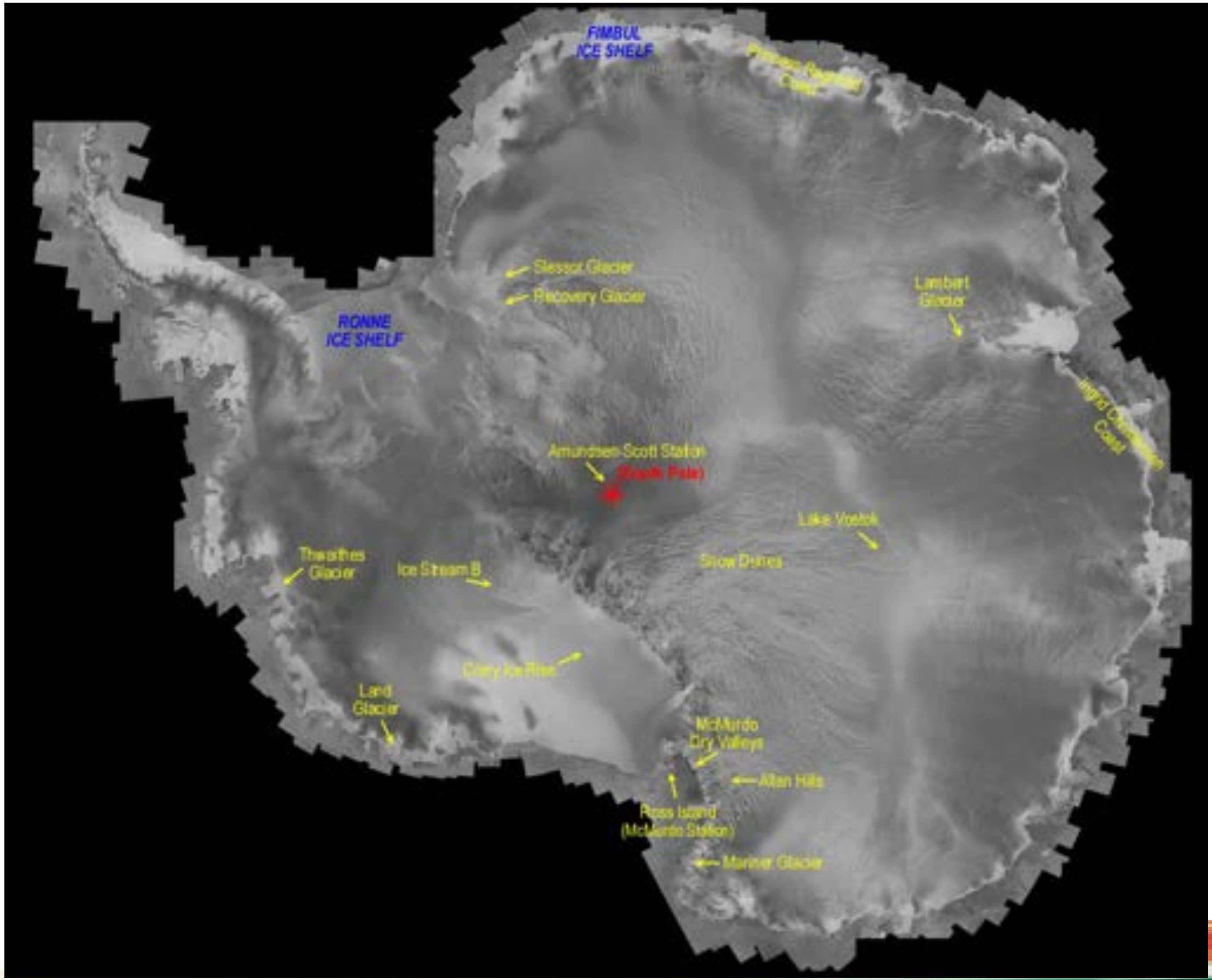




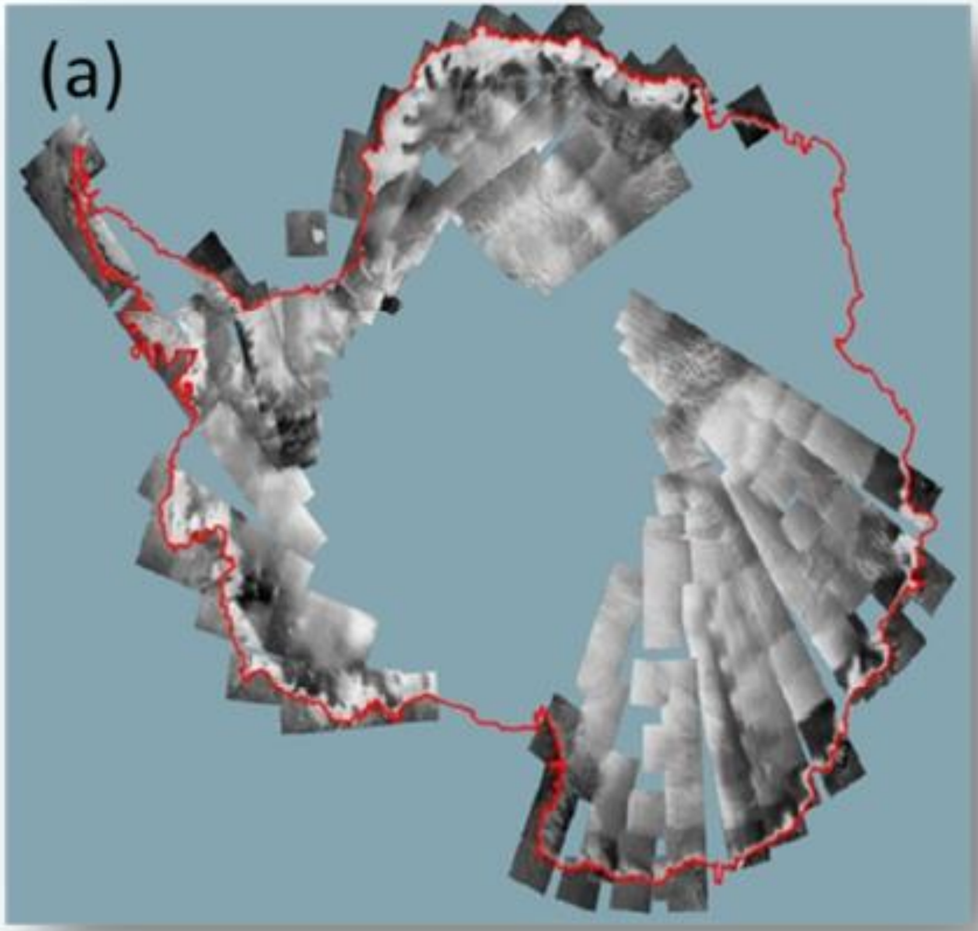
Issues: Lake depth, geotech parameters and good quality DEM data

Progress & Innovations in Remote Sensing of Polar Cryosphere

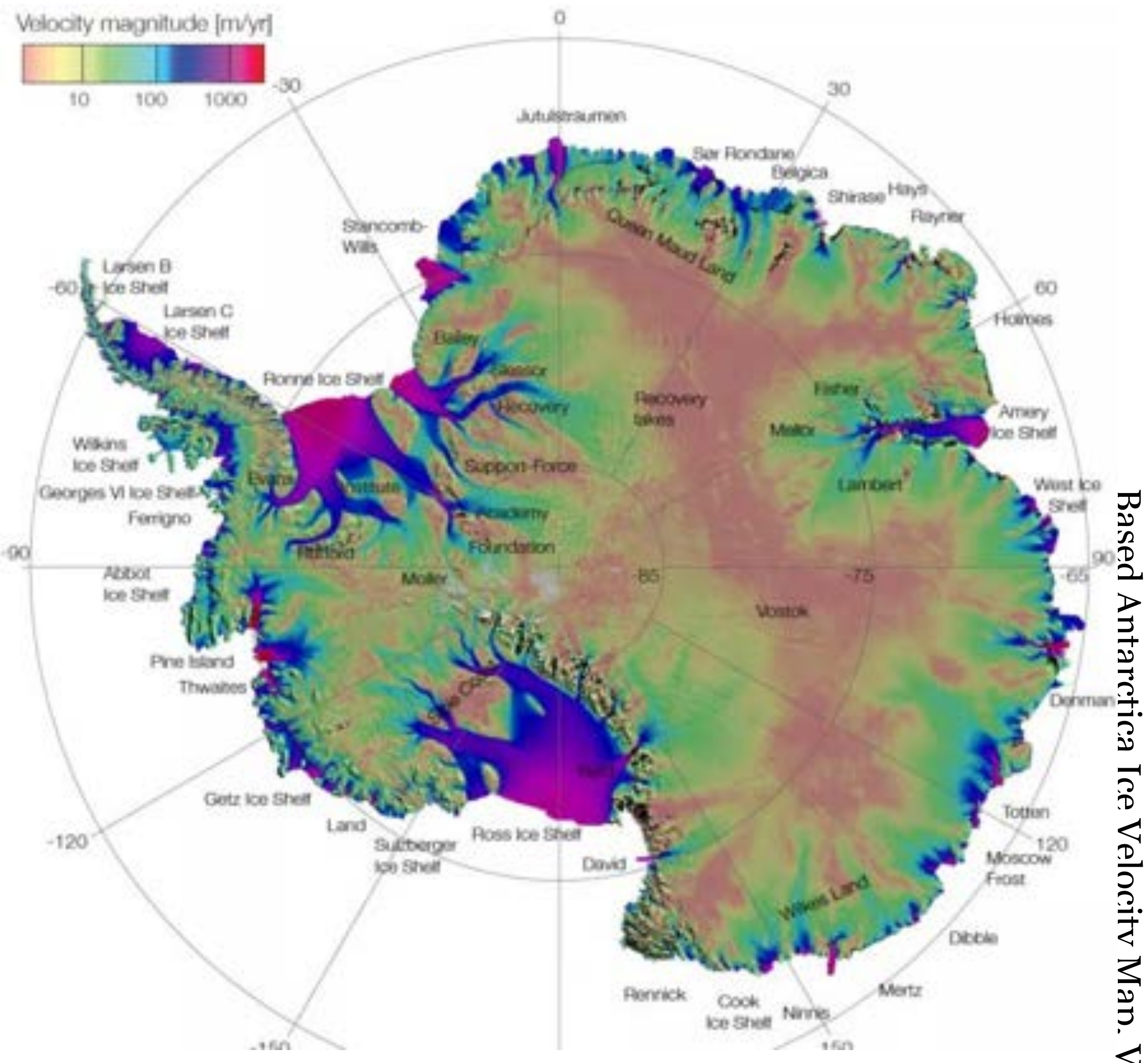
Radarsat mosaic of Antarctica as part of RAMP project



ISRO's RISAT-1 partial mosaic of Antarctica



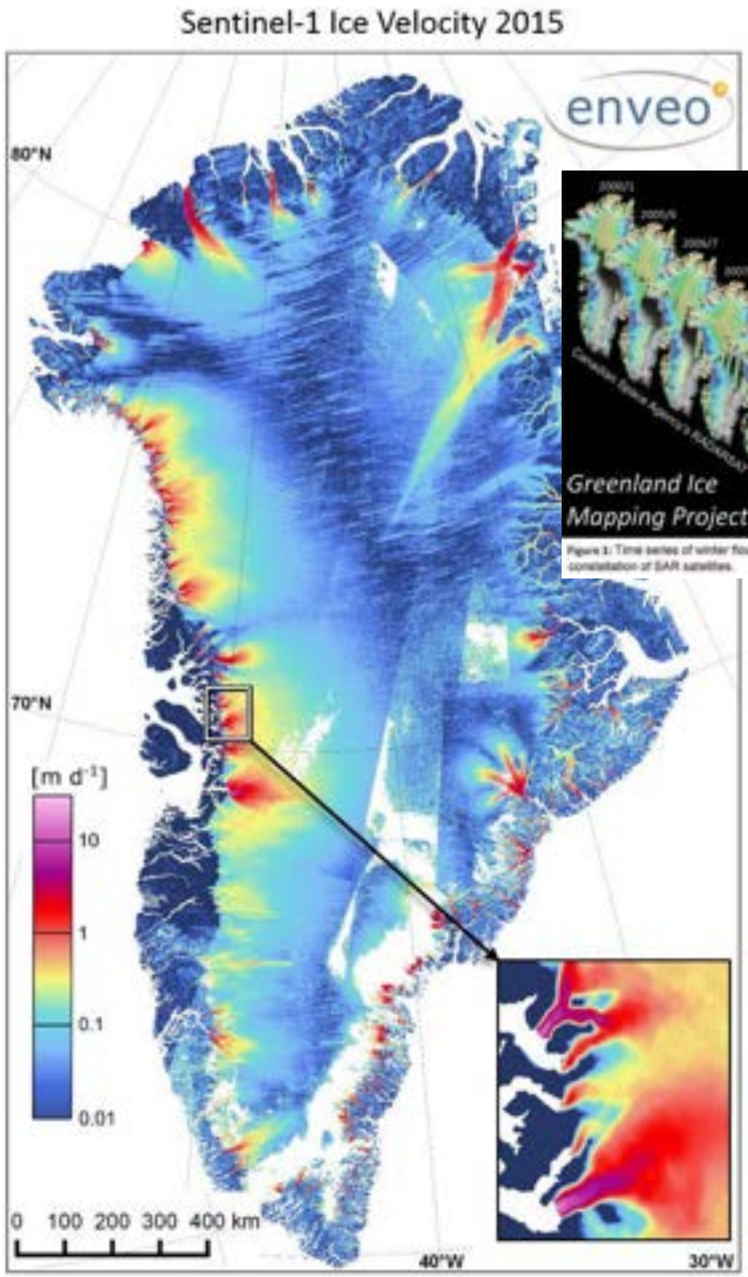
SAR data for Antarctica ice velocity estimation
DInSAR and Feature/Offset tracking methods

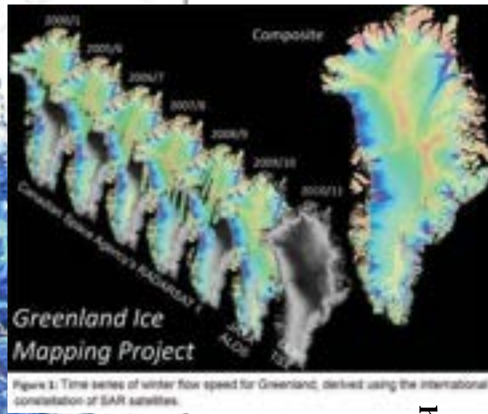


MEaSUREs InSAR-Based Antarctica Ice Velocity Map (nsidc-0484)
Source: NSIDC DAAC; Credit: AIV;

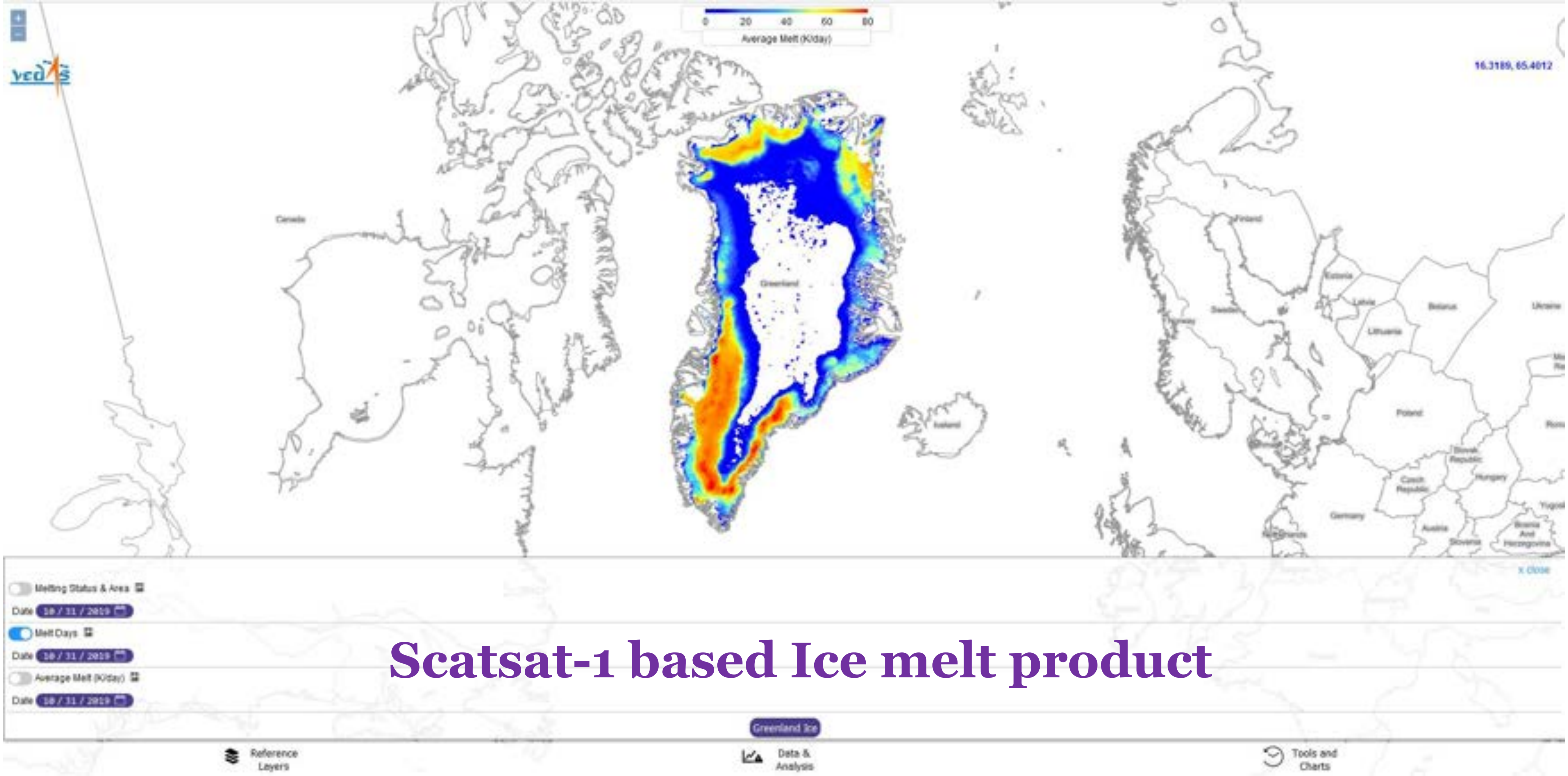
+ DInSAR and SAR based Grounding lines (nsidc-0498) and basin boundaries (nsidc-0709) of icesheets and ice shelf are also available

Making Earth System Data Records for Use in Research Environments (MEaSUREs), InSAR-Based Antarctica Ice Velocity Map. V-2





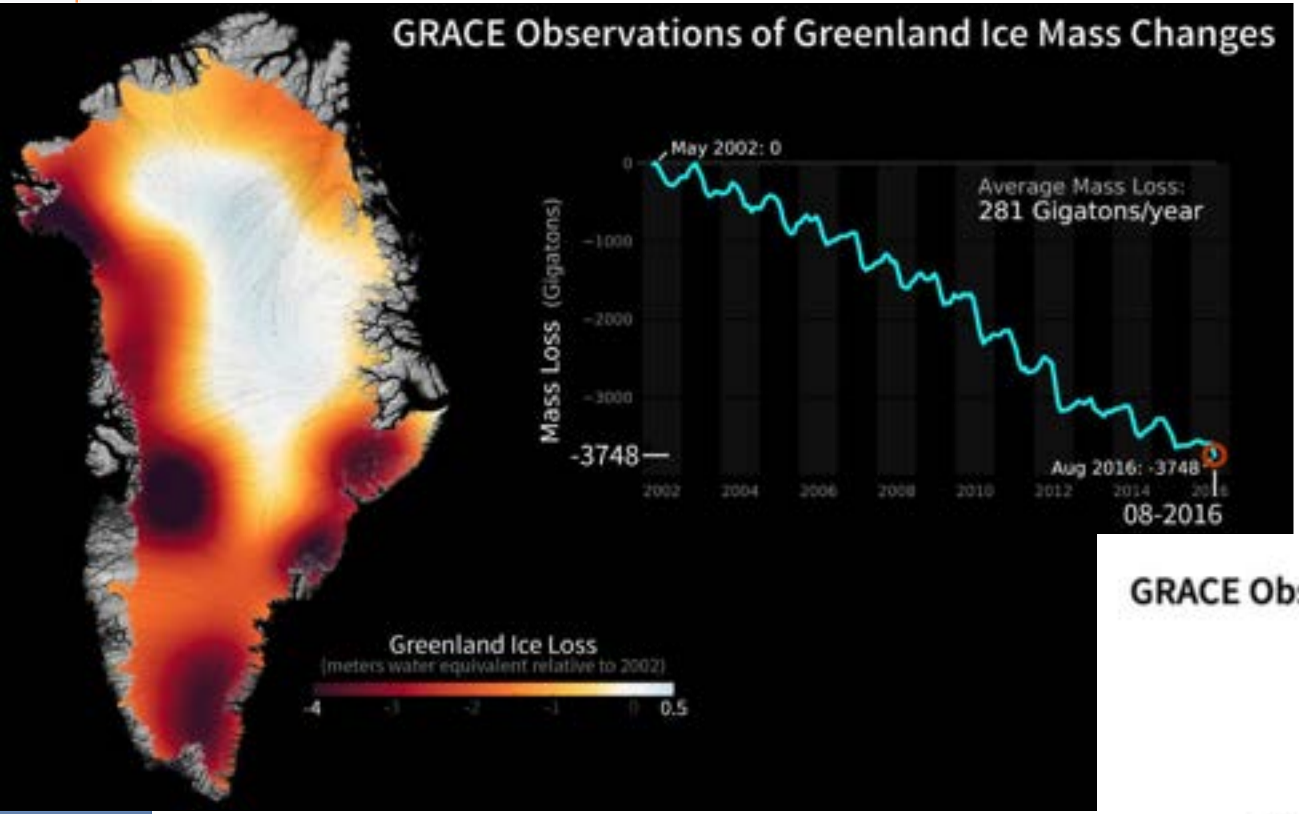
http://nsidc.org/data/docs/measures/nsidc0478_joughin/

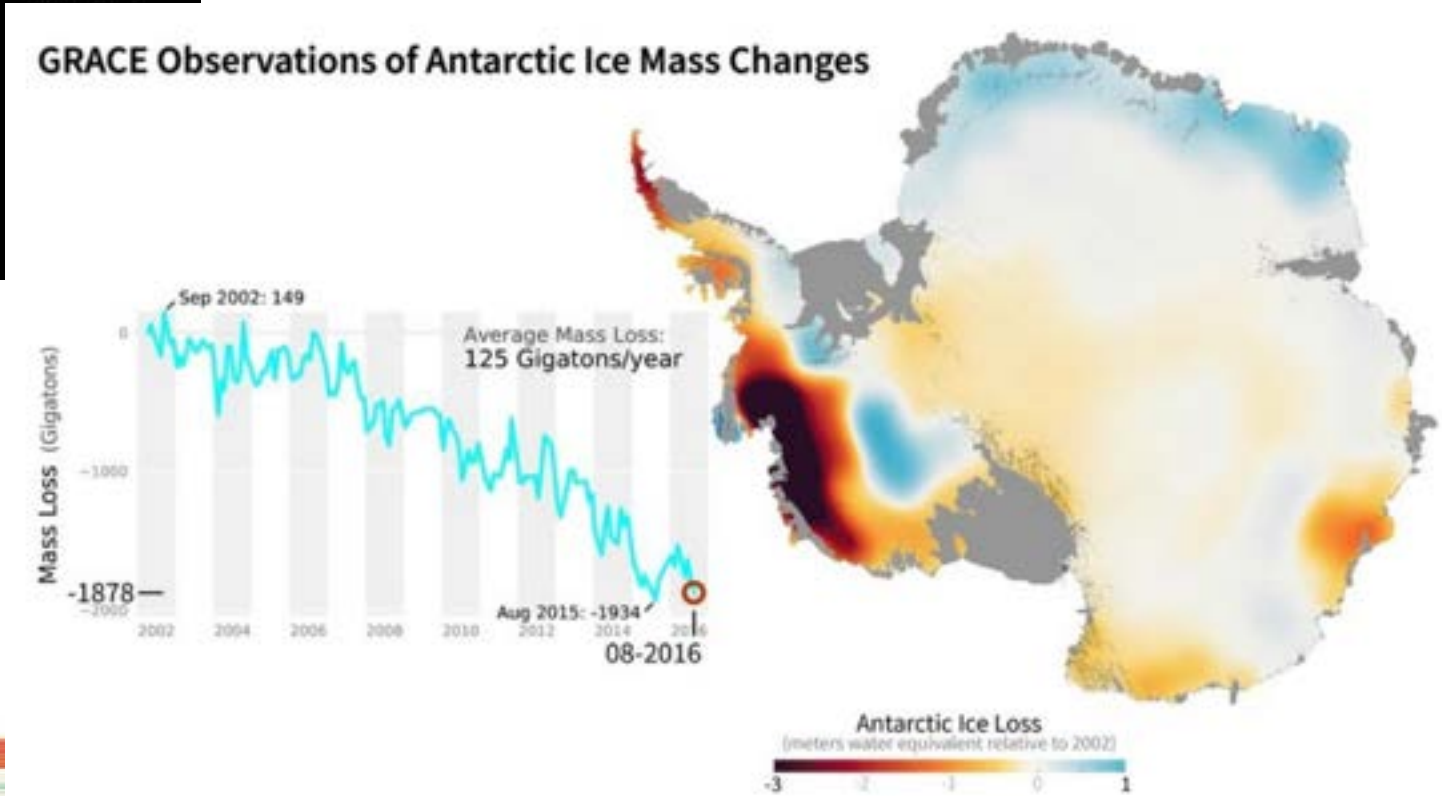


Scatsat-1 based Ice melt product

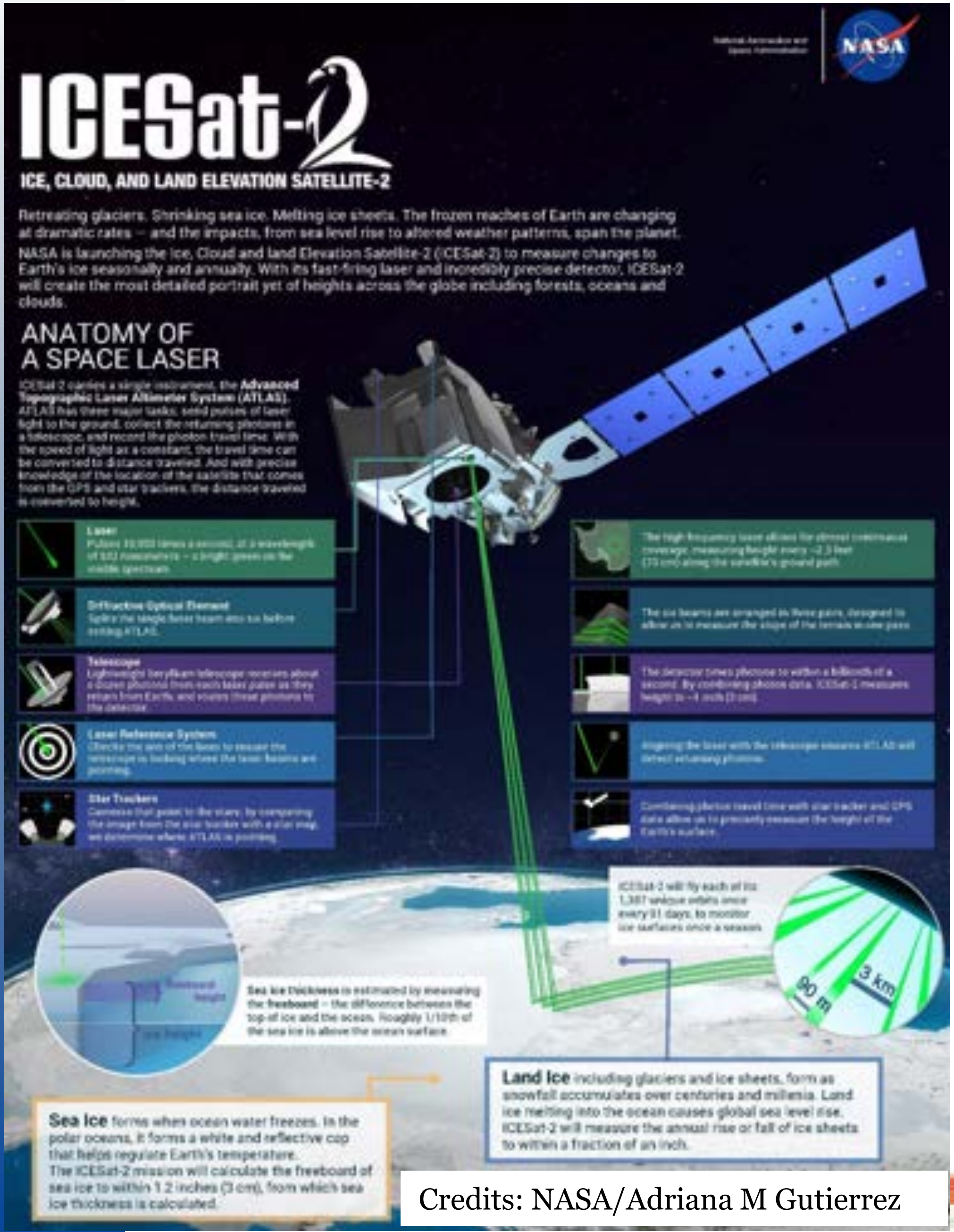
https://vedas.sac.gov.in/vstatic/greenland_ice/index.html

Gravity based measurements for polar ice mass

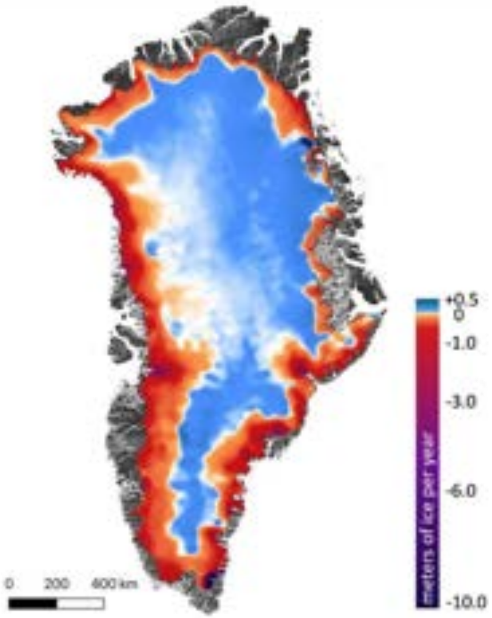


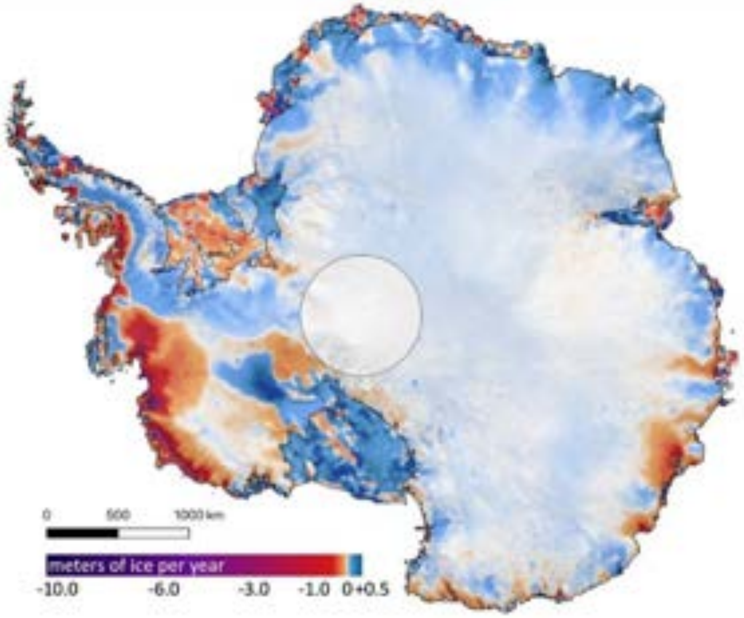


Progress in Space LIDAR based observations of cryosphere



Credits: NASA/Adriana M Gutierrez





(Smith et al. / Science / AAAS via UW)

https://nsidc.org/data/icesat-2/products

SWOT -Surface Water and Ocean Topography mission has interesting applications for Cryosphere

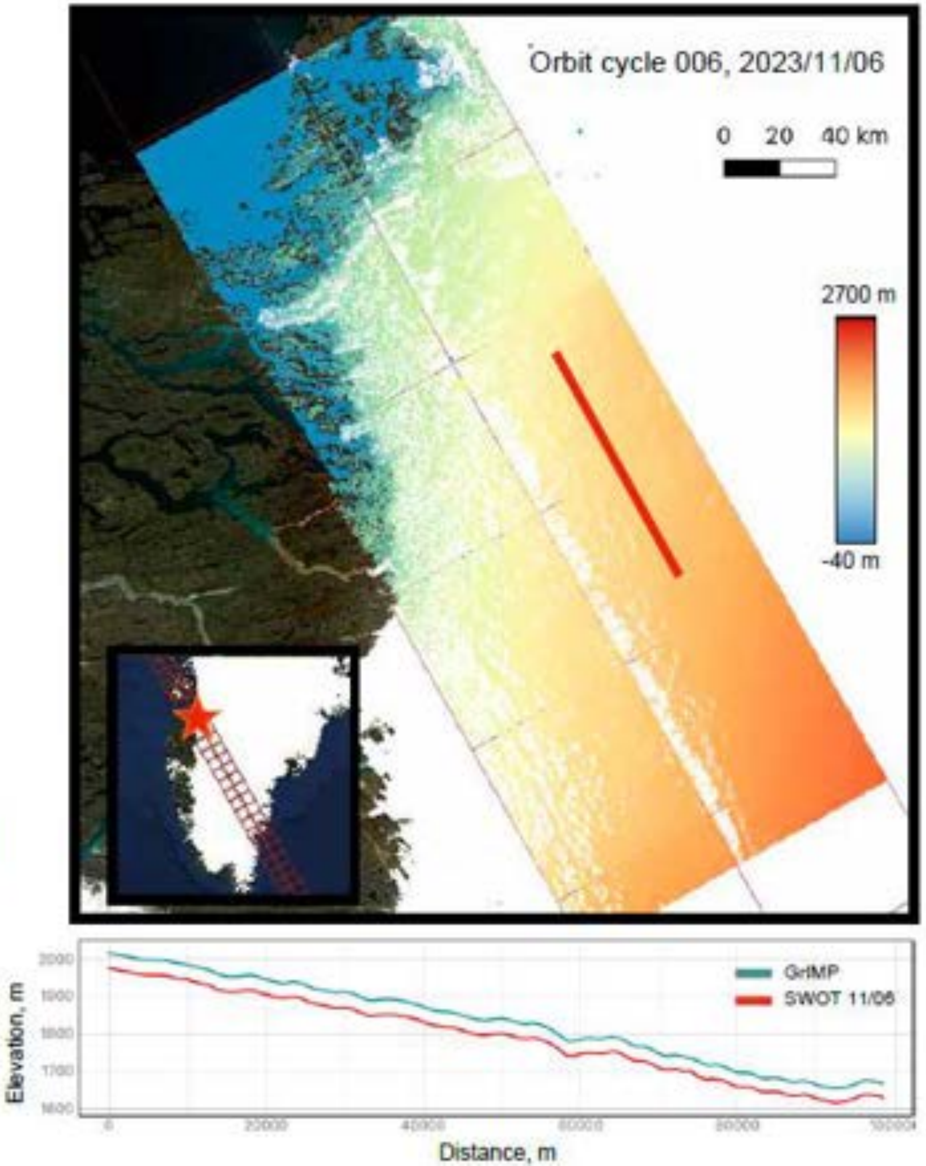
SWOT

Initial Results

Ice sheets/continental interiors

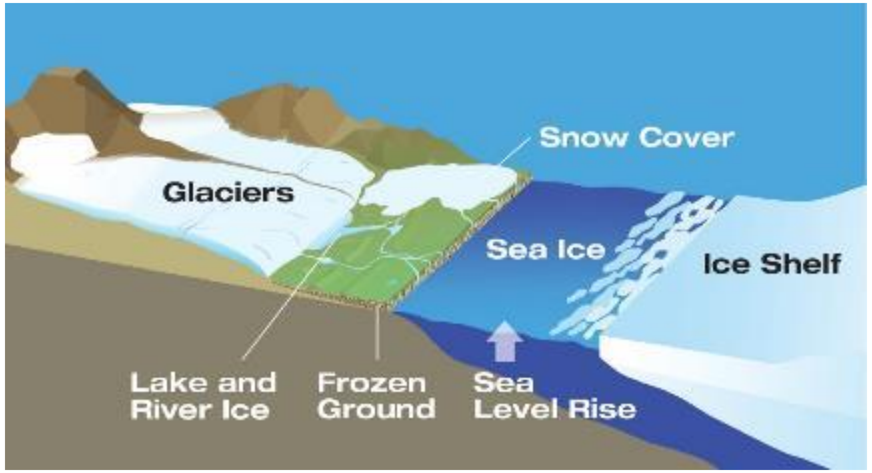
- L2_HR_Raster standard product successfully measures ice sheet elevations over Greenland interior
- All pixels included in the standard raster product were bright enough in radar backscatter to be detected as “water” by the high rate (HR) processing algorithms.
- Resultant elevations comparable to profile shape from Greenland Ice Mapping Project (GrIMP) DEM from 2019-2020 (I. Howat & Ohio State University, 2022).

For some cryosphere applications, may be able to use the standard HR high -level products "off the shelf"



4 (Stuurman et al, AGU 2023)

Future Innovative EO Missions for Cryosphere Studies



Dual freq. SAR SAR, L-band and S-band SAR, for Solid Earth, Biomass and Cryosphere studies

CRISTAL (Copernicus Polar Ice and Snow Topography Altimeter)

1. To measure and monitor the variability of Arctic and Southern Ocean sea-ice thickness and its snow depth.

2. To measure and monitor the surface elevation and changes therein of glaciers, ice caps and the Antarctic and Greenland ice sheets.

Interferometric Radar altimeter for Ice and Snow (IRIS)

Thermal infraRed Imaging Satellite for High-resolution Natural resource Assessment (TRISHNA): Indo-French mission

Ecosystem stress and water use (i.e. Monitoring of water & energy exchange of the continental biosphere).

Coastal and inland waters (i.e. monitoring of meso-scale, sub meso-scale dynamics).

Cryosphere: Snow and glacier melt runoff, debris detection in glaciers, dynamics of glacial lakes

Thanks and ??

https://www.iirs.gov.in/

praveen@iirsddn.ac.in